Durable Development of Oasis Beach

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Preface

The multidisciplinary project 'Durable Development of Oasis Beach' deals with securing sufficient recreational facilities at a beach sector near Varadero. This Cuban town hosts one of the largest tourist destinations in the Caribbean and is expected to grow even more. The ideal outcome of the project is a viable design that successfully combats the problems experienced at the Oasis Beach.

The project is part of the MSc programmes Hydraulic Engineering and Transport, Infrastructure & Logistics as provided by Delft University of Technology. Four students spent a total of three months on bringing this research to a successful end. Preparations for the stay abroad required more than the usual attention as Cuba is known for its connectivity issues. All necessary software licenses were obtained in the Netherlands and the larger part of the bibliography and auxiliary documents were pre-downloaded as well. Hereafter, a two month stay at the Cuban host university Universidad Tecnológica de la Habana José Antonio Echeverría (CUJAE) followed. This stay proved to be invaluable due to the possibility of direct contact with our supervisor prof. dr. L. F. Córdova as well as with experts from the Cuban engineering bureau Gamma.

The immersion in Cuban life was a very important aspect of this period apart from the wealth of experience acquired through conducting the project. The current cultural and political position of the island nation is unique in the world and gives plenty of food for thought.

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Acknowledgements

Firstly, we would like to take the opportunity to thank prof. Cordóva who was responsible for accommodating us in technical and personal needs during our time in Havana. Also, our thanks go out to our supervisors at home: ir. van Overeem, prof. dr. ir. Aarninkhof and dr. ir. A. Pel. Their support and guidance during this project was greatly appreciated, as was their technical input.

We would also like to acknowledge the contributions of Gamma Engineering (Havana) for sharing their specialist knowledge of the Oasis beach and the Institute of Oceanography (Havana) for allowing us to run our storm simulation on their supercomputer, saving us valuable time while in Cuba.

Our thanks go out to Deltares, who generously made their software available to us for use during our project and ARGOSS who granted us virtually unlimited access to their global offshore wave database. Finally, we are extremely grateful to Van Oord B.V. who helped us realise this project both financially and by sharing their technical and in-practice experience.

cujae

TU Delft

DIMI Delft Infrastructures & Mobility Initiative

GAMMA
TECNOLOGIA Y MEDIO AMBIENTE

BMT ARGOSS
"Where will our knowledge take you?"

INSMET
Instituto de Meteorología

Deltares
Enabling Delta Life

Van Oord
Marine ingenuity

Abstract

Storm safety and durability of touristic destinations is of utmost importance in Cuba, considering high stakes regarding life and capital invested in the development of the touristic sector. This two-month research focuses on one of the largest Caribbean beach tourism hotspots found in Varadero, Cuba.

Tourism along the Hicacos peninsula has been on the rise and will continue to do so. The Oasis beach hotel is capitalizing on this trend by building a larger new hotel. However, no characteristic flat white coral beach is present in front of it. Tourist demand is greatly driven by the presence of such a beach.

Year-round erosion was verified to be partly caused by a blocking of longshore sediment transport. The local harbour groyne at the eastern beach section was found to be responsible for this but may not be adapted, as it is a necessity for the harbour entrance. Demolition of existing hydraulic structures, construction of a groyne at the westward boundary and sand nourishing are proposed as a zero-solution to ensure sufficient beach width (40 metres) at the 800-metre coastal segment. Durability is not achieved through this zero-solution as the average lifetime between maintenance nourishments is smaller than one year.

This result shows that successful development of the Oasis beach sector can only be achieved by considering cross-shore erosion processes as well. An important aspect of the cross-shore transport was expected to be the effect of tropical storms on Oasis beach. To ensure the safety of tourists in storm conditions, an assessment of the infrastructure was required. A multidisciplinary path was chosen to ensure safety of inhabitants, tourists and capital, especially during hurricanes. Flood safety, coastal engineering, transport and infrastructure form the core pillars of the research.

Two distinct events were simulated to determine the morphodynamical response of the Oasis beach, namely hurricanes Wilma (2005) and Irma (2017). Both affected the northern coast of Cuba greatly, but passed Varadero from opposite directions. A general hurricane scenario was tested in evacuation assessments of the entire peninsula, which has just one exit road. Furthermore, the capacity of the current evacuation scheme was projected on the expected population and tourists visiting the peninsula in 2048.

Proposed coastal solutions were the construction of a submerged breakwater along the entire length of the beach, an artificial reef or a combination of the two. Normal, cold front and hurricane conditions were imposed upon these structures using XBeach software to test their performance. The subsequent infrastructural safety of the hinterlands was modelled using Simio software.

Results yielded good performance of the artificial reef against structural erosion from both the normal north-eastern wave climate and the northern cold front waves. The submerged breakwater performed better in hurricane conditions though extension of both groynes was found necessary to keep sediments within the Oasis beach system.

A multi criteria analysis was used to determine the best coastal intervention given the project requirements. Initially, no financial motives were used to determine the optimal solution. The results of this analysis stated a preference for the installation of an artificial reef. Its added recreational value was not quantified and thus not discounted from the initial investment. In detailed design, cost estimations of all viable design alternatives showed that the artificial reef was also a relatively affordable option.

The final recommended design that ensures beach durability thus consists of: demolition of weathered hydraulic structures, western groyne placement, initial nourishment, artificial reef deployment and maintenance nourishment for a 30-year lifetime. A modelling of the definitive design with, also including the vegetation of the dunes indicated the Oasis beach section to be flood safe. The total cost of this intervention amounts to approximately $900,000 and takes 28 months to complete. If monitored well, the artificial reef will increase its coastal defence capacities and functionality is expected to exceed the 30-year lifetime.

Recommendations regarding storm safety also include the evacuation process of tourists during the extreme hurricane conditions, on which the coastal design was based. Various projections of the growth of the number of tourists on the Hicacos peninsula have been simulated in a Simio evacuation transport model. The model indicated that even for the largest projected growth of tourism in Varadero, the infrastructure suffices and using a 50:50 ratio between evacuees being transported in buses and cars, it is possible to evacuate the peninsula in twenty-four hours.

To be able to evacuate using this optimal ratio, an increase in car ownership in Cuba is required before 2048, as a shortage exists in the current situation. Therefore, the peninsula is still considered storm-safe, but monitoring of the actual increase in tourists is advised.

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Lexicon

Δ	Specific gravity	-
a_b	Share of buses	-
ADCIRC	Advanced Circulation Modelling	
Autopista	Highway	
B	Crest width	m
C	Chézy smoothness coefficient	$m^{1/2}\ s^{-1}$
c_0	Offshore wave celerity	$m\ s^{-1}$
Cayos	Keys, islets	
C_d	Drag coefficient	-
C_{pae}	Capacity share of personal vehicles	h^{-1}
CUC	Cuban convertible peso	
CUP	Cuban peso	
C_{vh}	Road vehicle capacity	h^{-1}
D_{50}	Median grainsize diameter	m
d_{n50}	Nominal median block diameter	m
e	Effective height factor	-
F	Tidal form factor	-
f_{pae}	Share of personal vehicles	h^{-1}
H_i	Incoming wave height	m
hPa	Hectopascals (air pressure)	hPa
H_s	Significant wave height	m
h_t	Hard structure toe depth	m
H_t	Transmitted wave height	m
K_t	Wave transmission coefficient	-
L_0	Offshore wavelength	m
MCA	Multi criteria analysis	
MSL	Mean sea level	m
N	Number of waves	-
N_s	Hard structure stability number	-
P	Notional permeability	-
r	Roughness height	mm
R_c	Breakwater freeboard	m
Re	Reynolds number	-
S	Damage level	-
s_m	Fictitious wave steepness	-
SWAN	Short Wave Analysis Nearshore	
t	Hard structure layer thickness, time	m, s
T_m	Mean wave period	s
T_p	Peak wave period	s
V_n	Nourished volume	m^3
w_s	Sediment fall velocity	$m\ s^{-1}$
XBeach	eXtreme Beach behaviour (software)	
α	Slope of hard structure	-
η	Seawater deflection from mean sea level	m
ν	Kinematic viscosity of seawater	$m^2\ s^{-1}$
ξ_c	Critical Irribarren parameter	-
ξ_s	Irribarren parameter	-
ϱ_s	Sediment density	$kg\ m^{-3}$
ϱ_w	Seawater density	$kg\ m^{-3}$
Φ	Wentworth soil classification number	-

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1. Introduction

This section will firstly provide the physical and social context of the project. From the context the necessity and scope of the project will be derived. To conclude this section, the methodology provides an outline to the following analyses and the program of demands specifies the functions the final design will need to fulfil.

1.1 Cuba in general

History

The history of the Cuban pre-colonial era remains rather obscure, mainly due to the swift disappearance of the native inhabitants after the arrival of Cristopher Columbus in 1492. The Cuban indigenous population were decimated in a matter of years by foreign diseases, violence and slave labour. This created a demand for the Spanish rulers to repopulate the island, as its sugar plantations provided a precious cash crop at the time. Africa was found to be the ideal source of slave workers and this African heritage can be seen in many Cubans still today.

At the end of the nineteenth century, Cuba was amongst the last nations to be subjugated by European imperialism and slavery. This did not fare well with the newly-arrived beacon of democracy, the United States of America, just 200 kilometres from its shores. An intervention war was fought, and the US claimed an easy victory, replacing the Spanish regime.

Due to the prohibition of alcohol in the 1930s in the USA, Cuba became a rum-fuelled casino fantasy for many Americans, and the Mafia was happy to invest their money, laundering it at the same time.

When it became apparent to the Cuban population that their country was not only run by a dictator but by an American mob-affiliated and corrupted dictator, an uprising was the next logical step towards sovereignty. The 1959 revolution of Fidel Castro successfully overthrew the regime and it did not take him long to find a new ally in the Soviet Union. Despite the collapse of most socialist states in the 1990s and the legalisation of the US Dollar as usable currency, the Castro regime has sustained its governmental structure until today (2018). (Amara, Christiansen, & Dedio, 2017)

Economy & politics

Economics and decision-making are heavily intertwined in Cuba. Many aspects of daily life are still State-run and private enterprises are a rarity. The role of such an omnipresent government will have a big effect on construction works like the development of the Oasis sector. The exact structure and influence of the Cuban government will be discussed in the stakeholder analysis (section 2.1).

Investments in Cuba are almost exclusively made using public funds. Private investors play a minor role, as the state owns most hotel chains and transportation providers. This generally means investments aim to profit the development of Cuba. The investments in tourism, which include the scope of this specific project, are paid using state revenue from the touristic industry. The result of this system is a relatively closed market, which develops by reinvesting profit in new hotels, beaches, and other facilities.

Geography

Cuba is the largest island in the Caribbean and part of the archipelago known as the Greater Antilles. The nation consists of some 4000 islands and cays (Hails et al., 2006) but the majority of its surface area is comprised of mainland Cuba and Isla de la Juventud (Knight & Levinson, 2018). Cuba shares its only land border at the controversial site of Guantanamo Bay Naval Base with the US.

Figure 1.1: Cuba

Like many other Caribbean islands, Cuba is famous for its sprawling beaches. Most of these beaches can be found along the northern coast, whereas the southern side of the island is known for its mangroves. The tectonic movement of the Caribbean and North American plates is responsible for this difference in appearance. The slightly elevated northern side of the island causes most rivers to flow towards the Caribbean Sea rather than the Atlantic Ocean. Hence, alluvial sediment is in short supply on the northern side of Cuba.

Climate

The Cuban climate can be characterised as mildly tropical. North-eastern trade winds moderate the average temperature range to a minimum of 23.1 ˚C in January and a maximum of 27 ˚C in July. Furthermore, three seasons can be distinguished namely (Cuba Weather, 2018):

- Dry season: November-April
- Wet season: May-October
- Storm season: June-November (European Commission, 2018)

These periods can vary locally but give a good indication for the whole of Cuba. Most precipitation can be expected during the wet season and especially in the overlapping period of the storm season. In this five-month period, the probability of hurricane occurrence is very high. The eastern part of Cuba is located close to the common trajectory of these extreme weather events but in some cases the storms reach the western part of the island (where Havana is located) as well, this is discussed in more detail in section 2.4.3.

Tourism

The past, present and future of Cuban tourism are important in establishing the relevance of the project. An outline follows below.

In literature, there is a consensus that Cuba underwent three distinct periods of tourism that differ significantly from one another. These can be described as follows (González, et al., 2013);

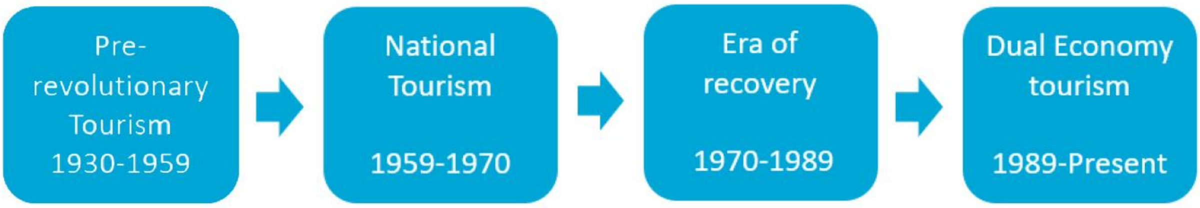


Figure 1.2: The three periods of tourism in Cuba

More or less amiable relations existed with the United States before the revolution in 1959. Foreign investments were legal at the time and it is commonly accepted that the regime during this era received payments from clandestine sources for the construction of e.g. casinos and hotels. This unsustainable system was replaced with an isolationist one by the post-revolutionary regime. Nationalisation of the economy made the foreign investors leave through the backdoor and record-low visits of down to 3000 foreign visits were recorded for over a decade (Sharply & Knight, 2009). Cuban tourism took on a new shape at the start of the seventies revealing itself as a sound strategy to decrease dependency on sugar exports, this lasted until the collapse of the Soviet Union. The 90s were marked by a collapse of the Cuban economy when many of its allies overthrew their socialist regimes. The legalisation of the US dollar as a currency and the need of attracting foreign currency for recovery of the economy is a process that is ongoing as of 2018. The current system in which tourism is facilitated has a duality between the Cuban government and a smaller share of private enterprises. A more detailed description of the interconnection of these roles can be found in section 2.1, the stakeholder analysis.

As of 2017, Cuba is the third-most visited destination in the Caribbean behind the Dominican Republic and Puerto Rico with over four million visitors annually. This growth is expected to continue (Fitzgerald, 2017), but in a less explosive manner as observed in the early 2000s. The reasoning behind this is that prices for accommodations have sky-rocketed due to low supply, but a rise in quality of touristic value did not follow (Sharply & Knight, 2009). Nevertheless, the increasing foreign arrivals need to be facilitated and a key player in the process is the Hicacos Peninsula near Varadero. The beach destination is responsible for roughly 60% of the income from tourism in Cuba. (Feinberg & Newfarmer, 2016) (Cuba Debate, 2017) The motivation of a visit to Varadero is found to be very singular, per 2017 a total of 1.7 million tourists found their way to the peninsula to enjoy its world-renowned beaches.

1.2 Peninsula de Hicacos

Geography

De peninsula de Hicacos is positioned in the north of the province Matanzas at approximately 130 kilometres from the capital Havana and 30 kilometres from the city of Matanzas. It is known for its beautiful and almost uninterrupted 22 kilometres long sandy beach and the many tourist hotels. With a maximum width of 500 metres, the peninsula can be called rather narrow (Luis Fermín Córdova, 2016).

Despite its suggestive shape, the peninsula was not formed as a spit. Spit formation would indicate a surplus of alongshore sediment transport, which is not the case. Instead, the peninsula is formed out of multiple smaller islands (cayos), which were merged due to centuries of sedimentation between them.

Tourism in Varadero

The first signs of tourism arose in the late nineteenth century when Varadero, the only town on the peninsula, was first recognized by the elite. In 1875, the first hotel was built, which is better known now as club Nautico. Even tough more tourists were getting familiar with the Peninsula through the decades, the tourist boom only occurred at the end of last century, after Fidel Castro opened the country for foreigners. Nowadays, the peninsula is clustered with 4 and 5-star hotels to keep up with the growing demand. Annually, the Hicacos peninsula is visited by 1.7 million visitors (Cuba Debate, 2017).

Infrastructure

The main highway along the north Matanzas coast changes names from Via Blanca to Via Rapida when traversing Varadero. Exiting the Via Blanca brings vehicles on the Autopista Sur, which starts along the Paso Malo marina and connects the entire peninsula to the main land. The highway has two lanes in both directions and is mostly used by bus operators for transfers to the airport and vice versa. The Autopista Sur is the only main road which runs along the peninsula and is regularly crossed by sideroads.

1.3 Oasis Beach sector

The Oasis beach sector is located at the very beginning of the Peninsula de Hicacos (See Figure 1.3). Note the rotation of the image as depicted by the north indicator, this was done for ease of visualisation.

Figure 1.3: The Oasis Beach sector

Orientation

A coordinate system is defined for the project 'Durable Development of the Oasis beach'. This will ensure an unambiguous use of orientations and reduce the risk of definition errors. The coordinate system is given in Figure 1.4. All coordinate systems used in models will refer to this system by means of a rotation of the axis.

The y-axis and x-axis are in line with respectively the northern and eastern direction. The origin is located at the Western boundary of the Oasis beach. The coastline is orientated under a small angle α with respect to the x-axis, defined positive counter clockwise, and is set at 5°. Coordinates of local reference system UTM Cuba North, the local coordinate system, are used to define locations.

When text refers to cross-shore, shore normal, longshore and shore parallel orientations, an anti-clockwise rotation of 5 degrees is consequently implied.

Figure 1.4: General coordinate system

Beach condition

A relation can be found between the beach erosion and human activity around Varadero. The first information about counteracting measurements for beach erosion dates to the previous century. Nourishments already started in the year 1967. After two inefficient attempts, in 1978 a comprehensive study was initiated to gain more insight in the coastal processes. This led to a mitigation plan in 1987. From that moment on, more effective nourishment where executed, but the structural erosion problem remained (Schwartz, 1991).

In 1956 the Canal Paso Malo was built, adjacent to the Oasis beach, to provide the fishermen with a shorter route to open sea. To protect the canal against siltation a breakwater was constructed on each side. Thirty years later the effect of the constructed breakwaters was described: "The Canal entrance on the north is bracketed by two jetties, both projecting more than 100 metres towards the sea, and starting sand deposition on the up-drift side of the longshore current and erosion on the down-drift side" (Montero & Marti, 1996).

Furthermore, to cope with the increasing number of tourists and their demands, hotels, houses and other structures are been built near or even on the beach. Those hard structures tend to reflect the incoming waves and thereby prevent the suspended sediments from settling. This results in a higher off-shore sediment flow than normal. As an attempt for solving the erosion problem the Oasis beach was nourished and hard structures were put in place. The sediment for the nourishment was mined along the Varadero beach, from accreting sectors. Ultimately, this resulted in the depletion of the natural reserves and in the long-term lead to beach instability (Montero & Marti, 1996). The hard structures found on the Oasis beach are currently in poor condition, and are even causing erosion in parts of Oasis due to reflection and secondary currents. Human activities are not the only source of trouble for the beaches. Natural phenomena like storms also contribute to the erosion of the Varadero beaches.

Natural events like severe storms are not new to the Cuba and her beaches. Most tropical storms occur from June till November as mentioned in section 1.1, with peak intensities occurring in September and October. During such an event, a cross-shore flow transports sediment from the beach to deeper waters. In equilibrium conditions, the eroded beach is restored during calmer conditions. However, due to the described human activities, the beaches of Varadero will not restore to its previous size.

Because of the importance of beaches for Cuban tourism and therefore the economy of Cuba, the government implemented the following regulations to limit the erosion rates:

- Limiting sand mining along the Varadero peninsula to small quantities, only to be taken from structurally accreting areas.
- Prohibiting construction inside the dynamic area of the beach (defined as the beach and dunes) for other purposes than the protection of the beach.
- Buildings damaged or lost to natural wear or storm damage in this area may not automatically be restored. It is preferred to demolish and relocate out of the dynamic area.

However, the above described regulations target symptoms, rather than solve the general problem. Therefore, most beaches still suffer from a retreating shoreline and need nourishments to retain sufficient beach width to facilitate the tourists, visiting the area. Figure 1.5 shows the construction and legislative developments, which led to the current state of the Oasis beach.

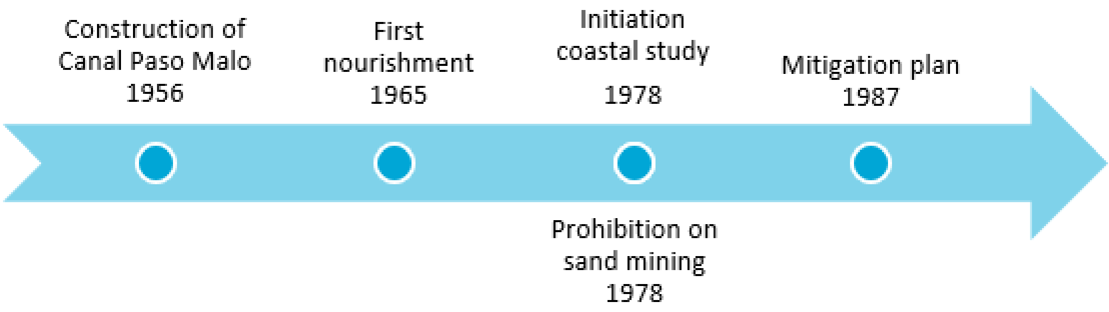


Figure 1.5: Developments in treatment of Oasis beach

1.4 Project scope

Problem description

Tourism in Cuba has been growing significantly the past last years. As this growth is expected to continue, the Cuban government is currently preparing for at least 10 million visitors in 2030 (Feinberg & Newfarmer, 2016). Varadero is one of the tourist hotspots in Cuba and provides for 60% of the income from tourism. With 1.7 million tourist visitors in 2017 it serves almost 40% of the total 4.7 million tourists visiting Cuba. Therefore, the Cuban government plans to develop new hotels in the Varadero area to keep up with the growing demand.

For this reason, the Oasis Beach hotel will be constructed near the Oasis Beach sector. However, the peninsula Hicacos suffers from beach erosion due to various causes. The Oasis Beach is even more susceptible to this than other areas, as the foreshore profile is much steeper than elsewhere. Therefore, the beach at the Oasis sector shows patches of exposed rock and little sediment is left. The hotel will not be attractive for beach tourism if this beach is not recovered, so for the hotel to be profitable the beach needs to be restored and stabilised. To keep the beach stable after restauration, all conditions to which the beach is exposed need to be considered.

Cuba lies close to several common hurricane paths. Therefore, the country often suffers damage from such events. Apart from causing damage to the hotels, these hurricanes also result in beach erosion, and temporary blockage of the road infrastructure of Varadero. The isolation of tourists on the Hicacos peninsula during hurricanes can result in dangerous situations for the Cuban population and the visiting tourists. Hurricanes thus provide essential input to the design conditions of the Oasis beach, but also require an assessment of the evacuation capacity of the infrastructure and available vehicles, to determine if the safety of the rising number of tourists can be guaranteed.

This project will focus on the rehabilitation of the Oasis Beach sector and the development of tourism on the Hicacos peninsula in a storm-safe manner. The effects of hurricanes are a central theme throughout both the coastal and evacuation transport disciplines in the project scope.

Focus by customer

To facilitate the growing number of tourists in Varadero during the coming years, the Cuban government focuses on expanding facilities for these tourists. Safety of the tourists needs to be guaranteed during all weather conditions, among which hurricanes require specific attention. Storms and cold fronts pose risks the assets on the Hicacos peninsula, specifically the beaches. The development of the Oasis beach must consider all weather conditions and their effects on the stability of the Oasis beach.

Problem definition

"To facilitate the expanding beach tourism of Oasis Beach without compromising the safety of tourists, inhabitants and capital in Varadero during both normal and storm conditions."

Project scope and limitations

This project focuses on the area in the north of Cuba, the town Varadero and the adjacent Peninsula de Hicacos. The development mainly focuses on the Oasis beach sector, an extension of the peninsula and Varadero town. The researched hydrodynamics and effects on morphology are considered from the offshore conditions through the landside dune foot of the Oasis sector. The hydrodynamics are considered in all weather conditions. To assure the safety of tourists and inhabitants, the evacuation capacity of infrastructure and transport modes on the Hicacos peninsula is assessed for safety during storm conditions.

Multiple engineering disciplines are required to successfully complete this project. As stated in the previous paragraph the project focus is put on safety and durability of (natural) capital in case of storm events. The safety of tourists and inhabitants and the resilience of the beachfront in hurricane conditions are the main drivers to keep the touristic growth safe and durable. The coastal erosion issues during extreme condition require knowledge of hydraulic engineering, specifically coastal engineering and flood protection. The optimization of the evacuation transport process during hurricane conditions requires knowledge of road and vehicle capacities.

This project is based on previous assessments of the Oasis beach sector and hydrodynamic data obtained by local experts. Some of the data of these researches will be adopted in this research after verification. Detailed hydrodynamic assessments using combined modelling of flow and waves are an important pillar of this project.

Solution scope

The solutions of this project will have to facilitate the growth of beach tourism in Varadero, while preserving the touristic qualities of the beach. This will require a minimum beach width of 40 metres along the 800 metres long Oasis sector and sufficient opportunity for evacuation in extreme storm conditions, which corresponds to a storm with a return period of 10 years.

The quality of the beach and the safety of the tourists cannot be compromised by the measures. This means the coastal measures must not be visible and the tourists should be able to travel and recreate with no additional risks due to the coastal or storm protection measures. The client has stated the preference to place minimal visible hard structure to improve the beaches, to prevent disruptions to the view as much as possible.

Goals of research

Firstly, this project will result in two detailed designs for the nourishment and protection of the Oasis beach sector, which will indicate their respective effectiveness on reducing the coastal erosion. The designs will include work plans, cost estimates and will use as much local materials and equipment as possible, to account for constructability. The designs will minimise visual nuisance to tourists enjoying the beach.

Secondly, this report will provide an assessment of the evacuation process and the required capacity for evacuation of the Hicacos peninsula, given the expected growth of tourism. The assessment will indicate whether current plans and means will still suffice for the foreseeable future, based on a range of possible growths of tourism.

Objectives

1. Ensuring sufficient beach area in the Oasis Beach sector

The first objective is to realize sufficient beach space along the 800 metres long Oasis sector, as recreation space for the guests of the Oasis hotel. A minimum is set at 40 m beach width.

2. Ensuring sufficient evacuation capacity

The second objective is to determine the required road and vehicle capacity to and from the hotels, to facilitate evacuation of the tourists on the Hicacos peninsula safely in hurricane conditions.

3. Ensuring storm safety of the Oasis Beach

This objective focuses on the protection of people and capital in the Oasis beach sector during storm conditions, considering the beach as both an asset and a flood protection system. Damages to the shoreline and hotel must be minimised for a normative storm with a frequency of occurrence of 1-in-10 years.

4. Prevention of visual pollution

Varadero has gained enormous popularity over time thanks to the pristine nature of its coastal features. The openness of the area is one of its most unique features. Losing this property may cause a decrease in overall popularity of the area. This uncertainty can be taken out of the equation by imposing the requirement to prevent visual pollution on the (new) Oasis Hotel beachfront. This limits the construction of emerged elements on the boundaries of the 800-metre segment. It also implies the compulsory demolition of any existing emerged structures, which are no longer in use.

5. Avoiding environmental nuisance

As the Oasis beach sector is only a part of the Hicacos area and neighbouring sectors have a recreational purpose as well, the coastal measures used must not shift erosion problem to another section of occupied coast. Furthermore, the proposed solutions must minimize disturbance to local tourism, biology and infrastructure during the execution phase.

1.5 Methodology

Storms and hurricanes are yearly returning events during the Caribbean storm season (see section 1.1) which cause a variety of problems ranging from nuisance to fatalities. In the scope of this project the addressed problems range from erosion and capital damage to flooding and ill-prepared evacuation, each carrying a different gravity of the consequences. All these situations will have a negative effect on Varadero beach tourism and are thus to be prevented. While total prevention of damage and inconvenience during storm events may be unachievable, possibilities for problem minimization are available. This will be done by combining hydraulic and transport engineering practices.

A lot of stakeholders are involved in developing the Oasis Beach sector alongside other improvements made to the Hicacos peninsula. It is important that all these stakeholders agree and are willing to work together to implement planned improvements. Therefore, a stakeholder analysis is done. Furthermore, there already have been researches to several Varadero beach areas, including the Oasis beach. A literature study on these projects is done to prevent overlap, gather useful information and establish the relevance of the current project.

In addition to the information gathered from previous reports, an updated coastal analysis is done for the Oasis Beach area. The current state and shape of the beach is described, wind conditions, sedimentology and oceanology are analysed. The hurricane conditions of Cuba are considered as well as the emergency evacuation planning before a hurricane. To prevent casualties, it is sometimes necessary to evacuate an area of Cuba. The analysis offers two in-practice examples of such events in the form of hurricanes Wilma (2005) and Irma (2017). To ensure safety of tourists and the population in Cuba it is important to have an efficient evacuation transport plan, to be able to transport all people in time. Therefore, a network analysis is done according to the evacuation transport framework model (Pel, 2017). In this analysis is determined what the population on the Hicacos peninsula and the number of movements during evacuation are, where they will be evacuated to, what mode and route will be used and how the traffic will flow. With this analysis and previous literature study on Cubans emergency plan will the critical infrastructure areas during storms and hurricanes be determined. Lastly, the wave conditions are analysed with the program ARGOSS in three different conditions; normal conditions, cold front conditions and hurricane conditions.

As a result of the literature study, two possible solutions for the durable development of the Oasis Beach area are selected based on the three situations considered in the wave condition analysis. Subsequently, two concept designs are made. The coastal analysis and the wave conditions analysis supply all relevant parameters and boundary conditions to ensure accurate modelling of changes in local hydrodynamics.

To determine the magnitude of the coastal erosion, storm conditions have been determined using an ADCIRC/SWAN-model. Using UNIBEST-CL+ and XBeach, the effects of various conditions on the coastline position have been quantified. The results of this study have been further analysed using Delft3d (Quickplot) and MATLAB, specifically the OpenEarth package. The models have been paired as shown in Figure 1.6. Blue arrows indicate indirect or reshaped input to a different type of model, black arrows indicate direct use of previous model input and/or output.

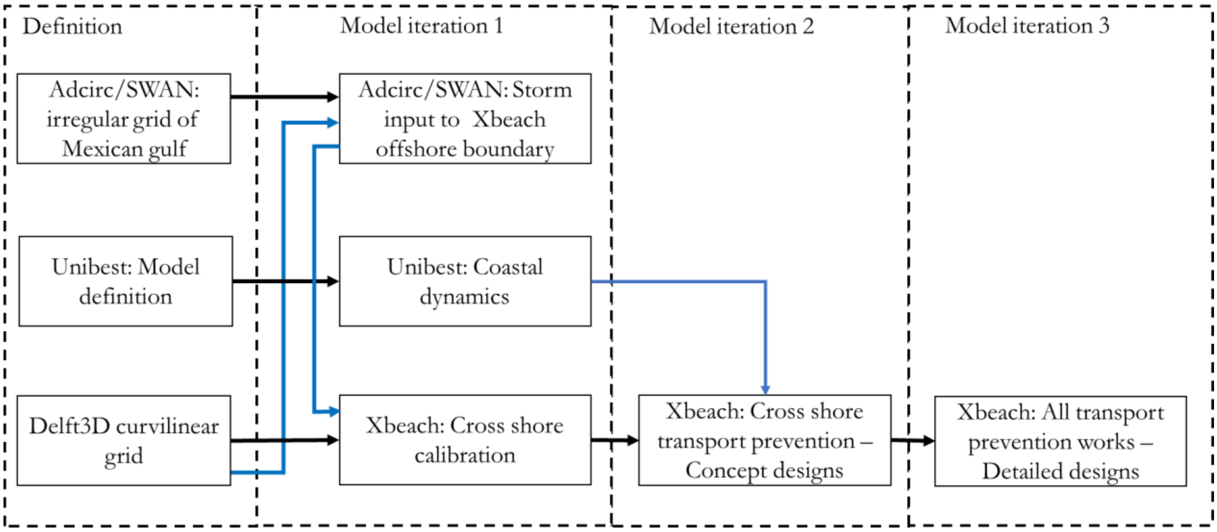


Figure 1.6: Coupling of coastal models

To determine whether in case of storm conditions the critical infrastructure areas will become a problem during evacuating the peninsula, a simulation model is made in the simulation program Simio.

These detailed coastal designs are yet again modelled using XBeach to test under the normal, cold front and storm situations. Data on hurricanes Wilma and Irma, two of the most severe hurricanes in recent Caribbean history, are used as storm input. The results from the simulated evacuation transport model for Varadero is divided into two parts. Firstly, the current situation is modelled to see if the current capacity and number of vehicles will suffice in evacuating everyone in time. Secondly, a scenario analysis is done with the help of three different forecasts in tourism growth. Simulating these scenarios show what will happen during future evacuations and critical points can be determined.

With the outcomes of the simulated models in XBeach and Simio, a combined intervention can be proposed. Advice can be given about the needed improvement regarding the evacuation process of the peninsula. Furthermore, the most suitable coastal interventions with respect to executability and wave energy dissipation can be put forward. To make the proposed solution operational on practical level a work method will be proposed and on basis of this work plan a detailed cost plan estimation is made.

The methodology is divided into four parts, as can been seen in Figure 1.7. These parts are:

1. Analysis
2. Modelling
3. Results
4. Solutions

The interrelation between the coastal and transport design mainly follows from the common driver they have, namely the influence of the storm conditions on the design. The structure of this report follows the phasing structure, followed by the overall conclusion and recommendations of the research project.

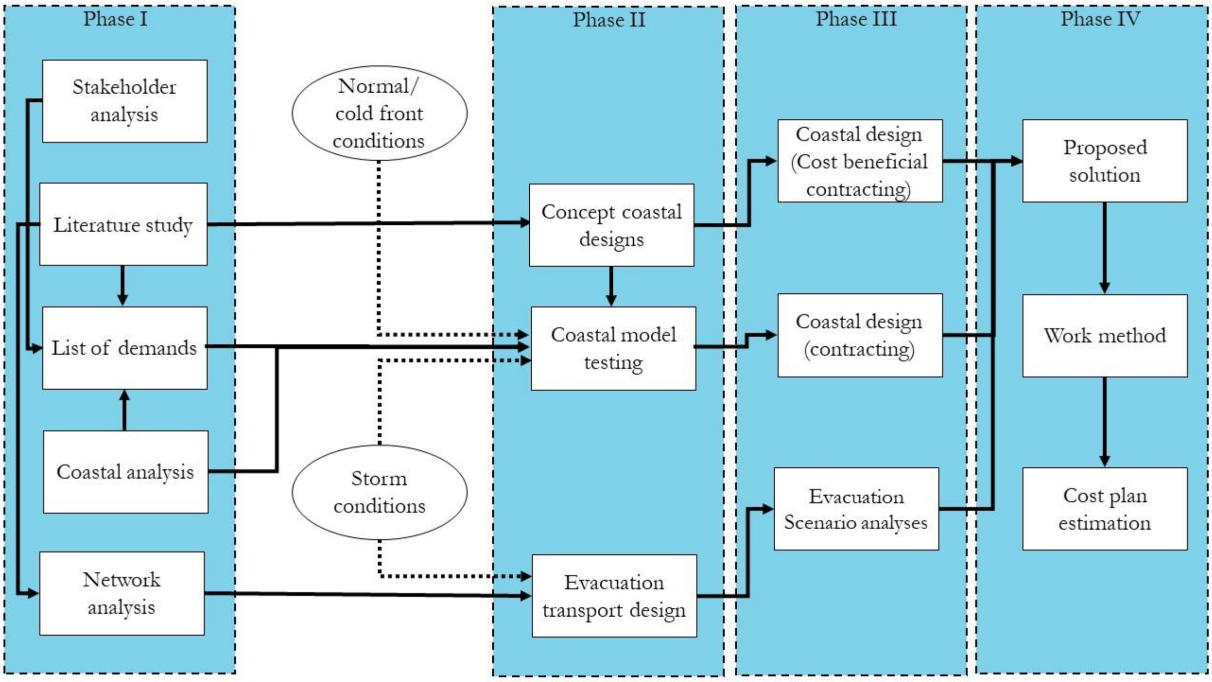


Figure 1.7: Structure of the report

1.6 Program of demands

The general objectives of the project have been described in section 1.5. These objectives are mostly functional and too abstract to directly test the design. The same holds for the interests of the stakeholders, described in section 2.1 and Appendix C. To assure the final design fulfils its required functions, this section specifies the demands, based on the client demands and stakeholder interests.

The demands will be verified in section 6.2.4 Verification of design, based on the final designs. As some specifications are further detailed by child nodes (e.g. S1. is detailed further by S1.1 through S1.4), they will be verified and validated through their child nodes and overall functionality. This means that the demand can be fulfilled by fulfilling its underlying demands and by a description of the overall functionality, showing that the underlying demands indeed proof the success of the top-level demand.

Beach development

B1. The solution must provide and protect a beach width of 40 metres along the entire Oasis beach section during the complete lifetime. Maintenance nourishment is allowed.

B2. Bedrock must be completely covered by a sandy layer from the dry beach through a water depth of three metres.

Safety

S1. Storm safety: The solution must be storm-safe, as specified by the underlying demands.

S1.1. The Oasis section must not flood in case of a normative, 1-in-ten-year storm.

S1.2. Hard structures must be stable during a normative, 1-in-ten-year storm.

S1.3. In case of a hurricane, sufficient transport modes must be facilitated for the evacuation of the increasing number of tourists on the Hicacos peninsula.

S1.4. Evacuation of the peninsula must be finished before the waves overtop onto the main road.

S2. Swim safety: The solution must be safe for recreational swimmers, as specified by the underlying demands.

S2.1 Return flows in the swimming area must be smaller than 0.20 m/s in normal conditions.

S2.2 The depth profile in the swimming area must be sloping predictably and gradually.

Constructability

C1. A solution which is constructible for Cuban contractors is preferred.

C2. For non-traditional solutions, the required external expertise must be indicated in the work method.

Lifetime and maintenance

L1. The solutions on Oasis beach need to fulfil their function during a lifetime of 30 years.

L2. Nourishments within lifetime are allowed but must be included in the total cost of ownership (TCO).

Interfaces

<u>I1. Physical</u>

I1.1 The old Oasis hotel building may or may not be demolished.

I1.2 The Paso Malo harbour entrance must not be closed.

I1.3 Expansion of the Autopista Sur is undesirable, due to the minimal physical space available.

I1.4 The proposed solution must not negatively affect the nearby beaches.

<u>I2. Logical</u>

I2.1 The solutions must be suitable for the expected tourist growth during the lifetime of the Oasis beach.

I2.2 The total cost of ownership (TCO) of the beach development may only be increased if this results in direct benefit to tourists in the form.

Boundary conditions

Bc1. The closest sand mining site lies near Cayo Mono, approximately 25 km from Oasis Beach.

Bc2. The following developments in design conditions over the Oasis beach lifetime must be considered:

Bc2.1 Sea level rise for the next 25 years.

Bc2.2 Trends in normal and storm conditions.

Product format

F1. All proposed final designs must include a work method and cost estimate.

Verification and Validation

To determine whether the final solution fulfils all specifications, a Verification and Validation cross-reference is included in Appendix B. This table lists all demands and objects and shows how the various objects in the design fulfil the specified demands. A column is added to include the motivation as to how the object fulfils the demand and whether any interaction between objects contributes to the successful fulfilment of the demand.

2. Analyses

This section gathers all information required to model the coastal and infrastructural situation. The first analyses made in this section provide the project context. The analyses of wind, wave and traffic flow provide input to model and design for the project demands.

2.1 Stakeholder analysis

It is necessary to be familiar with the most relevant stakeholders to the project given the complex economic and political situation in Cuba. Even more so, their individual power, interest and attitude towards the project must be mapped to gain understanding of the decision-making track. A stakeholder analysis is used to obtain this insight. The used definition of stakeholder is:

"*Any person, social entity or organization able to act on or exert influence on a decision.* "

- (Enserink et Al., 2010)

The following subsections describe the relevant stakeholders, their attitude towards the project and the general strategies to manage their opinions in the Oasis beach project. Lastly, a power-interest grid is given to see what role the stakeholders are playing in the search for the best solutions of the Oasis beach sector.

2.1.1 Stakeholder description

A wide range of stakeholders have a vested interest in this project. The project requires approval by various authorities and the input of several other parties to be successful. For all relevant stakeholders, their general goal and activities are described in this subsection.

National government

Ministry of Tourism (MINTUR)

The Ministry of Tourism is responsible for managing all services for tourists visiting Cuba. The main purposes of tourism include: beach, urban, eco- and medical tourism. This ministry owns approximately half the hotels (which are available to tourists) in Cuba, among which are the Islazul, Cubanacán and Grand Caribe hotel chains. (Hails et al., 2006)

Ministry of Construction (MoC)

The Ministry of Construction is responsible for the realization of all projects in Cuba. This ministry receives technical input from specialists of the Ministry of Science, Technology and Environment, as well as advice from engineering and research companies, predominantly Cuban, but also from abroad if needed. The ministry serves as the client during the construction and has direct contact with the contractor, similar to the role of Rijkswaterstaat in the Netherlands.

Ministry of Science, Technology and Environment (CITMA)

The Ministry of Science, Technology and Environment is involved in engineering and construction in Cuba in various ways. They focus on sustainable development of Cuba and have a long-term perspective on projects in general. For this project they are expected to focus on the influence of the measures on the coastal ecosystem, the adjacent beach sections and the water quality.

Ministry of Armed Forces (MINFAR)

The Revolutionary Armed Forces have been extremely influential throughout Cuba, ever since the Castro revolution. The ministry owns the largest tourist facility chain in Cuba, Gaviota, which falls under GAESA, the ministry asset management branch of the ministry. Gaviota is officially separated from the Ministry of Tourism, however, both parties generally share any plans for future expansion. Though the name of this ministry does not indicate it, this ministry not only governs the military, but also handles all economic affairs in Cuba.

Ministry of Labour and Social Security (MTSS)

The Ministry of Labour and Social Security controls the registrations of all employees of all companies in Cuba. As larger companies are subject to additional taxes on paid wages, the tourist sector is extremely important to them. No hotel can operate without formal approval and registration of staff by this ministry.

Ministry of Transportation (MoT)

The ministry of Transportation is responsible for facilitating all transport of people and goods throughout Cuba. Any changes in touristic visits to an area are of interest to them, as these may require improvements to roads or public transport.

Banco Financiero Nacional

The national Bank of Cuba is one of the main provider of funds for construction projects. They are formally structured under the GAESA, which in its turn is a branch of the Revolutionary Armed Forces. The Cuban government plans to finance the expansion of tourist facilities predominantly by national revenue coming from tourism. Approximately 70% of the investment will come from domestic capital (Feinberg & Newfarmer, 2016). The Banco Financiero National will therefore be strongly involved in the construction and exploitation of the Oasis hotel and beach.

Parties operated by the government

Centre of Environmental Services of Matanzas

The Centre of Environmental Services of Matanzas enforces environmental regulations in the province of Matanzas. This institute researches the environmental state of the province Matanzas. One of their main activities is monitoring the coastal morphology of the Hicacos peninsula and to contract for small maintenance and nourishment activities. This institute also enforces environmental laws in Matanzas, under the authority of the provincial representative office of the Ministry of Science, Technology and Environment. (CITMA)

Institute for Physical Planning

The institute for Physical Planning controls all buildings in Cuba. To operate any business in a building in Cuba, this institute must approve the use of the building by giving an official permit for the use of the building. For hotels, these permits are usually arranged before the construction of the building and span longer periods of ten years or longer. Normally, these permits are renewed, and hotels are managed by the same (Cuban or non-Cuban) party for much longer ten years.

Real Estate holding Companies

The Real Estate holding Companies of the Cuban government are the official owners of the hotel buildings in Cuba. The leases given out by the Institute for Physical Planning to hotel chains allow the chains to operate the buildings, but the maintenance during the lease is still the responsibility of the holding Companies. The Real Estate holding companies are assigned annual budgets by the state. It is not uncommon for these budgets to run out, resulting in structural lack of maintenance to hotel rooms. This, in turn, causes rooms to remain vacant.

Hotel Operators

The hotels are operated by various parties. A large part falls under the Cuban government, either under the Ministry of Tourism or as a part of Gaviota, the chain of touristic facilities governed by the Revolutionary Armed Forces.

Gamma

Gamma Engineering is a Cuban engineering company, based in Havana. They have been involved in the development of the Oasis beach sector for over ten years. Their involvement so far included various types of research of the location, such as bed level soundings; granulometric research and advice on a preliminary design.

Department of Coastal Processes at the Institute of Oceanography

The institute of Oceanography conducts research into the tide, wave climate and other parameters in the Gulf of Mexico, which are relevant for engineering projects on the northern Cuban coast. The institute is based in Havana.

GAESA

GAESA is the Enterprise Administration Group of the Ministry of the Armed Forces. It manages both the Gaviota Hotel group and the other branches of the Gaviota tourism industries.

Gaviota

Gaviota is both the largest and the fastest growing party in Cuban tourism. Apart from holding the largest market share of state-owned hotel rooms, Gaviota operates bus lines, car rentals, marinas, shopping malls and retail outlets. It also organizes day trips and activities from its own tourist agency and is thus able to provide everything a tourist may need. All new hotels operated by Gaviota are financed by its profits, which GAESA stores in the Banco Financiero Nacional, which is another one of its assets. External investment in GAESA and thus Gaviota has not yet been welcomed.

Cuban Construction firms

The Cuban Construction firms are quite interested in the increase in tourism, as the growth of tourism provides them with a range of projects. The Cuban government strongly favours local contractors over international companies, as their investment in the Cuban economy is much needed.

Other

Municipality of Varadero

The municipality of Varadero represents the residents of the city of Varadero, who mostly work in the tourist sector or work indirectly for the tourist sector (such as construction workers performing large maintenance on the hotel buildings). The municipality tries to keep some of the profit of the tourism in Varadero.

Province of Matanzas

The province of Matanzas serves a similar role as the municipality of Varadero, but on a larger scale. The provincial representation of Matanzas is quite interested in the developments of the Varadero beach tourism, as they are responsible for small maintenance nourishments of the beaches and see potential profits in more touristic developments.

CUJAE

The CUJAE or the Universidad Polyténico José Antonio Echeverría de Havana regularly collaborates with several other engineering companies to provide specialist knowledge for the design of hydraulic engineering solutions. Professor Córdova of the CUJAE, who has over 30 years of experience at the university, is regularly involved in research and design for complex coastal projects.

External contractors

These are international companies who are interested in playing a part in the implementation of the construction plans for the Oasis sector. This can be for the nourishment of the beach, but also for the hard-structure work. These companies will do the work that will not be carried out by the Ministry of Construction. An example of an external contractor is the Dutch dredging specialist Van Oord.

External experts

External experts, unrelated to specific stakeholders, are mostly from engineering institutions around the world, have given their opinion about the situation in the Oasis sector. They have a professional interest in the Oasis sector, but no direct perspective of making profit.

Tourists

Includes all national and international tourists travelling to the province Matanzas, this can be either to Varadero Town, the Hicacos peninsula or the Oasis sector, for vacation reasons. The expectation is that the number of tourists will increase significantly during the coming years. They form the main source of income for this area.

Car rental companies

Cuba has a few car rental companies that rent cars to tourists. Currently, there is a limited number of cars that is available to be rented by the tourists. With the expected increase in tourists, the car rental companies will have to invest in expanding their car business to keep up with the demand.

Transport (bus, taxi) companies

Various transport companies are active in Cuba and many of them cater to tourists, as tourists in Cuba have a larger budget than the local communities. Therefore, the tourists are the clients, providing them with the most profit. To keep their customers satisfied they will need to extend their businesses to keep up with the growing tourism.

2.1.2 Organisational diagram

To create a clear overview of all stakeholders mentioned above, an organisational diagram is used. As can been seen in the diagram in Figure 2.1, all stakeholders are somehow related to the Cuban government. The colours indicate the position that stakeholders have concerning this project.

Every national ministry has a representative on regional level and besides these there are certain stakeholders that work for the ministries directly, serving specific administrative purposes. There are only a few stakeholders involved on local level, namely the tourists themselves and the municipality of Varadero. The Ministry of Tourism is responsible for the tourists and the municipality of Varadero is part of the Province Matanzas. Furthermore, certain stakeholders do not have vested interest in the project but may be consulted with the activities of other stakeholders. Other stakeholders want to participate actively in the implementation of the project and/or will directly gain profit from it.

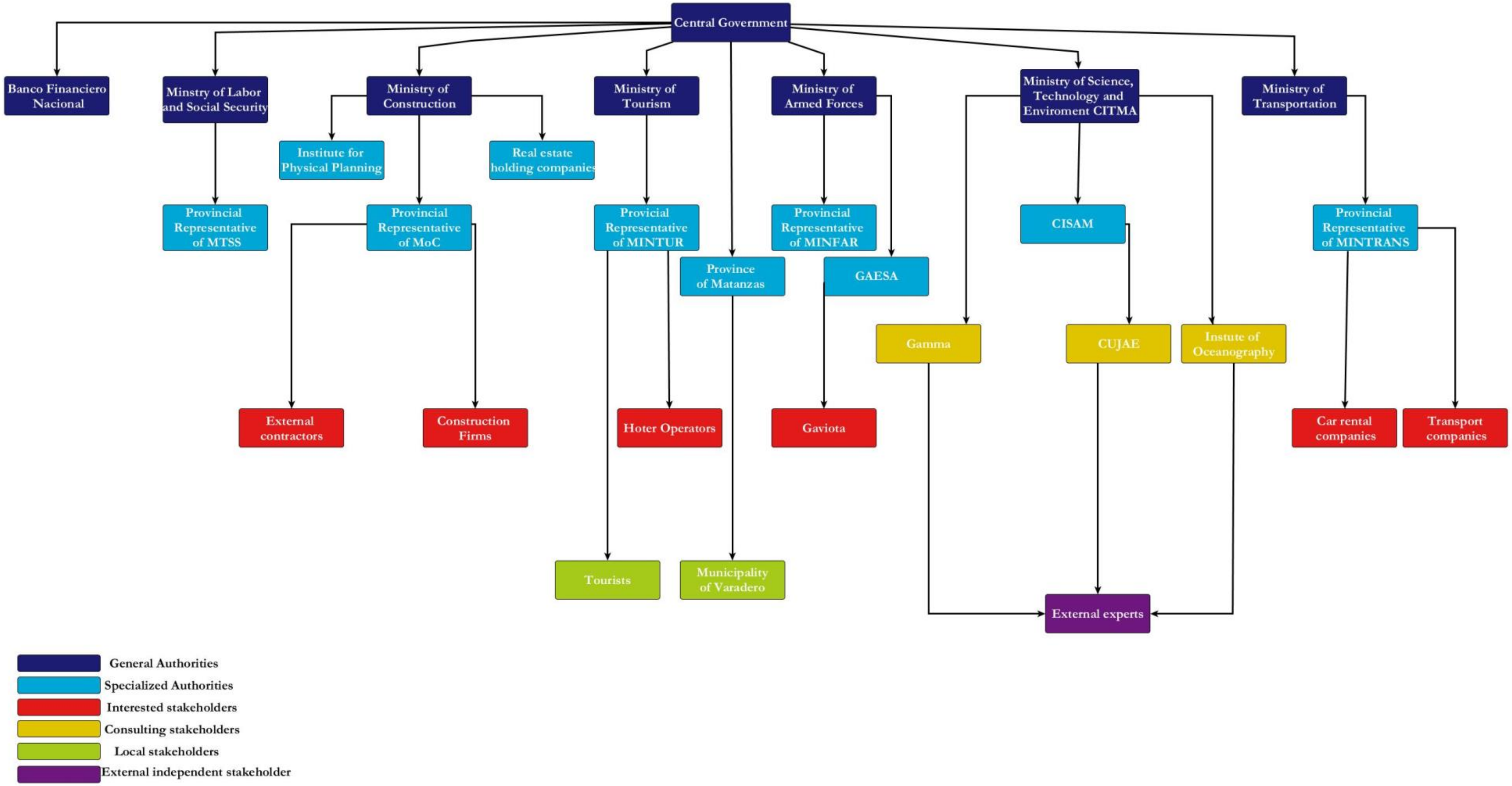


Figure 2.1: Organisational stakeholder diagram

2.1.3 Problem perception stakeholders

All stakeholders have some level of interest in the project and many of them have some authority in the decision-making process as well. To determine how to work with each of these stakeholders, firstly their perception of the problem is important.

In Appendix C all stakeholders are listed, and their general interests are expressed. As their interests are often abstract or not directly relevant to the project, a desired situation for the Oasis beach has been derived from these general interests. A comparison between this vision and the current situation results in the perceived 'gap' of the stakeholder, in other words: their perception of what is missing in the existing Oasis beach. The perceived gap and causes of this gap provide input to the scope of this project.

Finally, the appendix lists the proposed improvements to the Oasis sector or general Varadero area, which would suit the interests of the stakeholder. Combined with the relative power of the stakeholders, these improvements will be considered in the scope description in section 1.4.

2.1.4 Power-interest grid

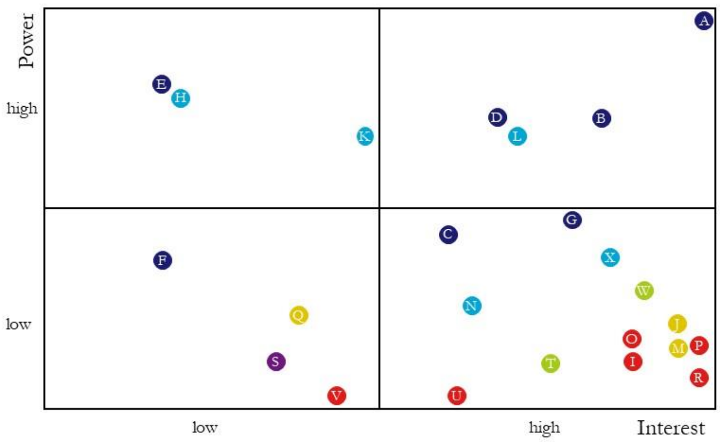
To determine how stakeholders must be treated in the development of this project, a power-interest grid has been developed, based on which the stakeholders can be categorised in one of four groups.

The first group is the group with both low interest and low authority in this project, the 'crowd'. The bottom left quarter of Figure 2.2 represents this group. Stakeholders in this category have little effect on the project. Their opinions may be relevant for the project, but they have little expectations of involvement in the project.

The second group, the 'subjects', have high interest in the project, but have little power. As Figure 2.2 clearly shows, a large variety of stakeholders appear in this group. Many of these parties hope to contribute to the construction or exploitation of the Oasis beach. These stakeholders must be informed about the project, at least until it is sure that their involvement is no longer required. For example, the construction companies are to be informed until the contractor has received the contract to build, whereas the hotel operators will have to be informed of the award of the exploitation contract and of any possible nuisance to adjacent resorts during the entire construction.

The top left quadrant shows the third group, the so called 'context setters'. These parties are ministries and their executive offices, whose authorisation will be needed to successfully complete the project, but they are not expected to participate actively in the project. The ministry of Social Services will have to authorise the worker's permits for the hotel and beach to be built and for the personnel of the hotel to be allowed to work. The institute for physical planning and the real estate holding companies will have to approve of the use of the building and agree on maintenance plans. They will only be involved at specific points in time but have the authority to stop the project at their decisive moments.

The fourth and most important quadrant shows the key players. These parties are actively involved throughout several phases of the development of the Oasis beach. The ministry of Tourism has decisive power over everything related to tourism, from project definition to exploitation and is thus the most important stakeholder to this project. The ministry of Construction serves as the client during the complete construction phase and will advise on acceptance of the project to the real estate holding companies upon transfer. Finally, CITMA and CESAM are extremely important in both design and construction, as they have the authority to stop the project if environmental regulations are not followed. These demands, as set by the key players, will be considered in design and construction.



A. Mintur
B. MoC
C. MINFAR
D. CITMA
E. MTSS
F. MINTRANS
G. BFN
H. Institute for Physical planning
I. Hotel operators
J. Gamma engineering
K. Real estate holding companies
L. CESAM
M. Institute of Oceanography
N. GAESA
O. Gaviota
P. Cuban Construction firms
Q. CUJAE
R. External Contractors
S. External experts
T. Tourists
U. Car rental companies
V. Transport companies
W. Municipality of Varadero
X. Province of Matanzas

Figure 2.2: Power-interest grid

2.2 Network Analysis

This section provides an analysis of the transport network in Varadero to gain insight in the consequences during an evacuation caused by storm or hurricane. This is done by evaluating and describing the network of the Hicacos peninsula and Varadero town, including the Oasis beach sector. The town Santa Marta is where the peninsula is connected to Cubans mainland and is the only other town within the scope of this project.

This network analysis focuses on an evacuation transport model. An evacuation transport model is in essence similar to a general transport model, with certain adaptions in context of evacuation. Travellers are for example unfamiliar with the situation and rely differently on expectations and information based on past experiences and the road capacity could be changed. The transport model consists of the following sub-models (Pel, 2017):

1. Trip generation
2. Trip distribution
3. Modal split
4. Traffic assignment
5. Traffic flow

The first four steps describe the travel choice behaviour of the involved people. The involved people in this network analysis include the inhabitants of Varadero, the employees working on the peninsula and the tourists. From now on this group of people is referred to as the population of the Hicacos peninsula. In the last step is the traffic flow process including all travellers predicted.

2.2.1 Trip generation

The first step is to determine how many people are involved in the network, to know the number of people that will need to be evacuated in times of emergency. Secondly, the number of daily movements made by the population is given per zone.

Currently, there are approximately 20,689 people (2017) living in Varadero (González, et al., 2013) (The Statistics Portal, 2018). However, besides its inhabitants Varadero is visited by many tourists each year. As stated in section 1.2, Varadero is known for its white beaches and attracts a lot of beach tourism. In 2017 a new record of visiting national and international tourists was set at 1.7 million, almost 40% of all tourists in Cuba (Cuba Debate, 2017). There are 54 accommodations available for tourists with a total of 20,162 rooms, containing 39,842 beds (ONEI, 2016). Thus, daily, there could be a maximum of 39,842 tourists on the peninsula.

Lastly, the employees of these accommodations and other touristic facilities do not live on the peninsula, they live within a radius of between 15 and 30 kilometres from their work (González, et al., 2013). In 2017, 123,500 jobs were generated by tourism, this is 2.4% of the total employment in Cuba (Word Travel & Tourism Council, March 2018). This includes only direct jobs like work in hotels or transportation services, it considered that at least 30% of these employees work on Varadero. However, Varadero covers 40% of the total tourists visiting Cuba and has a large part of all 4- and 5-star hotels, 30% is assumed because a part of the direct income from tourism is also generated by transportation services.

Table 2.1 gives a short overview of current total trip generation of the Hicacos peninsula and the Oasis Beach sector.

Table 2.1: Daily population of the Hicacos peninsula

	Daily (persons)
Inhabitants	20,689
Employees	37,050
Tourism	39,842
Total	97,579

To determine the trip generation on the peninsula, the area is divided into five different zones based on the deviation of the population. The subdivision is shown in Figure 2.3;

1. The latter half of the peninsula from the cross point of the Autopista Sur and Avenida Las Americas.
2. The second half of Varadero town
3. The first half of Varadero town
4. The part of Varadero town south of the Autopista Sur
5. The beginning of the peninsula from the canal Paso Malo till Calle 17 in Varadero Town.

Figure 2.3: The peninsula divided in five zones

The distribution of the population, which is evacuated from the peninsula to the mainland, is determined per zone. For this distribution the housing capacity and position of the hotels and houses is used. Zone 1 is an area with hotels only, in which no houses are present. Therefore, the movements from zone 1 tot the mainland are only made by tourists and employees. Zone 2, 3 and 4 are zones on the north side of the Autopista Sur, consisting of the houses in Varadero town and hotels on the coastline, so trips are made by inhabitants, employees and tourists. Zone 5 is the part of Varadero town south of the Autopista Sur, consisting of mainly houses and one small hotel, which is neglected due to the small contribution on the number of tourists. The distribution of the employees is based on the distribution of tourists. The number of trips generated during evacuation to the mainland is represented for each zone in Table 2.2.

Table 2.2:The trip generation of the Hicacos peninsula

Zone	Inhabitants [%]	Inhabitants [Number]	Employees [%]	Employees [Number]	Tourists [%]	Tourists [Number]
1	-	-	30	11,115	30	11,953
2	35	7,241	20	7,410	20	7,968
3	35	7,241	20	7,410	20	7,968
4	20	4,138	30	11,115	30	11,953
5	10	2,069	-	-	-	-

2.2.2 Trip distribution

In this step the trips generated by the locals (inhabitants of Varadero and employees) and tourists are determined. Because the network analysis focuses on transport during evacuation, the trip distribution in normal circumstances is not considered. By evacuation transport modelling, trip distribution is used to see where the people will evacuate to in cases of emergency. If a hurricane threatens to hit Varadero, it is likely that the whole peninsula needs to be evacuated. Because of its narrow shape and the fact that it is surrounded by the sea, it is very sensitive to flooding. Therefore, the people will need to be taken to higher grounds.

As can be seen in Figure 2.4 the peninsula is connected to the mainland by one road leading to a town called Santa Marta and the highway Via Blanca. The Via Blanca leads to the city Matanzas and the highway Via Rapida leads to the city Cardenas through Santa Marta. The people without relatives or friends in safe areas will be transported to prepared shelters. Santa Marta is the closest town to the peninsula, but if the peninsula needs to be evacuated it is not likely that this town is sufficiently far from the hurricane track to be considered safe. Therefore, it is assumed that the tourists and locals without other places to go to, will be brought to the bigger cities Cardenas or Matanzas. Evacuees will be spread across these cities, depending on the capacity of these shelters to take evacuated people in.

Figure 2.4: The town Santa Marta at the beginning of the Peninsula Hicacos

2.2.3 Transport modes

There are four types of transport systems available around Varadero: air, rail, road and water. These systems are used by different modalities and have different kind of infrastructure. Nevertheless, water, rail and air will not be considered. Water is only used by fishermen and small pleasure yachts, rail in Varadero only functions as conveyance for freight and air is not used within Varadero, which leaves road as only and most important transport system. So, in case of evacuation all transport will be done via road. The road infrastructure is used by private and rental cars, taxis, buses, bicycles and (carriage) horses. Because bicycles and (carriage) horses are used in minimal amounts, this category is merged with pedestrian.

Private car

For a long period, it was not possible for Cubans to own a private car, due to the political history of Cuba. Every car was government-owned and could only be used by people employed by the government. (Warren & Enoch, 2010) Hence, there are still little private cars on the roads, nowadays 38 out 1000 people own a motor vehicle of which only 21 are passenger vehicles (Morales, 2017).

A second form of use of cars is by renting them out to tourists. The car rental companies are all owned by the government and has the authorisation to rent cars (NovelaCuba, 2018). Nevertheless, because of the limited availability of cars in Cuba there is still only a small market in rental cars.

Taxi

Taxis are important road users in Cuba. They are used by both tourists and inhabitants of Varadero. All taxis belong to the government, competition between different companies is non-existent, but there is competition between the individual taxi drivers (On the right wheels, 2018). Taxis are used in two different ways, as private taxis and as convective taxi. Private taxis are taxis used by one person or group of persons per time. Most of the taxis are used as convective taxi, this can best be compared as a combination of carpooling and hitchhiking. The taxi driver picks up people and whenever other persons have similar destinations, they can join. To get in, the taxi must be waved at. Sometimes the taxi driver uses hand signals to make clear if there are places available in his car, but most of the time he stops directly whenever there are still places available in his vehicle. They also use the claxon to let someone know that they want to drive that person.

Figure 2.5 shows several taxis; the taxi can be either classic cars or modern vehicles.

Figure 2.5: Taxis in Cuba

Bus

Besides taxis, buses are the second large road users. There are four different kind of buses driving at and around the peninsula. In 2015, nearly 60 percent of all passenger trips in Cuba are made with buses (Morales, 2017) .

Firstly, there is the local bus, used as public transport through Varadero and its neighbouring villages. This is done by Transmetro (Figure 2.6) this bus can be used by locals and tourists and has stations after every several hundred metres. These buses do not drive on a fixed schedule, but they have a fixed route. Transmetro uses a combination of touring cars and city buses, the touring cars have a capacity of around 55 seats and the capacity of city buses is estimated at 100 persons (Dalstra Reizen, 2018).

Figure 2.6: Transmetro bus for public transport and Omnibus Nacional

Secondly, the Omnibus Nacional, see Figure 2.6. This bus can only be used by Cubans and drives between cities, for example from Varadero to Havana or Cardenas. Tickets can be bought by a central ticket station, either on days beforehand or last-minute. These buses drive to and from Varadero on fixed times, four times a day. The buses have a capacity that is equally to a standard touring car of 56 persons inclusive driver. (Dalstra Reizen, 2018)

Thirdly, buses of the company Viazul (Figure 2.7). These buses drive equally as the Omnibus between larger cities or areas, like Varadero or Trinidad and tickets can be bought at the central station. Difference with the Omnibus Nacional is that these are mostly used by tourists and they all start or end in Havana. The buses that are used have a capacity of 55 persons and a driver. Just like the Omnibus Nacional they have a fixed time schedule and drive four times a day from and to Varadero.

Figure 2.7: Viazul bus and Transtur bus

Lastly, the buses of large tourist operators like Cubanacán or Gaviota. These buses can only be used by tourist. They are often booked as tour or as a trip from hotel to hotel. Tickets can be bought at tourist agencies or at hotels. Figure 2.7 gives an example of a bus from Cubanacán. The schedule of these buses depends on the tourism season, during high season they have more trips to Varadero than during low season, because there are fewer bookings. The companies use two types of buses to transport their passengers. One is a touring car with the capacity of 56 persons and the other is a smaller touring car with capacity of 30 persons.

Pedestrian

If the destination is in walking distance, the locals will do this afoot. Tourists will incline faster to take the taxi, thanks to its low prices. However, inhabitants also tend to share a taxi or take a bus, as they are not that expensive. Bikes are rare and are only used by locals. The horse and carriage in Varadero are either used as touristic attraction, guided tours around the island, or for fieldwork.

2.2.4 Traffic assignment

In the fourth step of the transport evacuation model the routes used for the trip distribution with different modes will be analysed. In evacuation transport modelling this means that the route that will be used to evacuate will be determined.

Figure 2.8: The road infrastructure of Varadero and surroundings

Road

Road infrastructure on and near the peninsula is limited. In Figure 2.8 the highway "Autopista Sur" is depicted. It is the main road and runs along the entire peninsula, coloured orange. On the northern half of the peninsula, only a handful of local roads exist besides this highway. The village Varadero has more local roads and the Avenida Primera, a somewhat bigger road on the north side (yellow road in Figure 2.8). The capacity of the local roads is rather small and mostly used for transport within the town, for larger distances the Autopista Sur is used. Therefore, the highway is the most important road containing the highest capacity.

On the mainland, the "Autopista Sur" is divided into the highway "Via Blanca" to Havana and the regional road "Via Rapida" through Santa Marta. The road infrastructure in Santa Marta also consists of local roads with the Via Tra as somewhat larger road.

The condition of the roads differs per area and per road type. The highway "Via Blanca" for example is for Cuban standards in good condition, the same holds for the "Autopista Sur". They consist of paved roads with minor damages every now and then. The local roads are mostly in worse conditions, most of them are paved, but some are not (Trading Economics, 2008). They are more worn-out than the highways as expressed by the greater density of flaws and holes.

Reason for the conditions of the infrastructure is aging and lack of maintenance during the years. Most roads are over 50 years old and little maintenance is done (Warren & Enoch, 2010)

Route

The highway is the most important road; hence it will play the biggest role during evacuations. Everyone who needs to be evacuated from the peninsula will go if needed via some local roads over the highway to the mainland. Afterwards, they will either be transported to shelters in Santa Marta, or via the highways to other bigger cities like Havana or Matanzas, depending on the availability and the size of the risks area.

However, there could be some difficulties during the evacuation. Firstly, the highways are located near the coast, which makes it prone to floods. Furthermore, capacity can become an issue considered that the whole peninsula, the Oasis beach sector and if needed the city Santa Marta must be evacuated over that same single highway.

Currently, congestion is not existing under normal circumstances, a positive side effect of the lack of availability of vehicles. There is a possibility this could change whenever the Alert Phase of the disaster reduction plan is set as described in section 2.4.3.

2.2.5 Traffic flow

As mentioned in the previous section there is currently no congestion on the highways during normal circumstances. It is to be whether this is also the case during the second phase of the emergency disaster reduction plan, when everyone on the peninsula needs to be evacuated to the mainland. Furthermore, it is important to determine whether the infrastructure will be sufficient to cover the expected increase in tourism and the development of the peninsula. The fifth and last step of the evacuation transport model is described in this section, namely the traffic flow. (Pel, 2017). The critical infrastructure areas for the transport network will be determined by the capacity of the current road and the critical water heights. During the determination of the critical areas, the expected growth in tourism and inhabitants is considered.

Capacity

As described in the traffic assignment, the highways are the most interesting roads in the concerned area; the Hicacos peninsula and the town Santa Marta. The local roads on the peninsula are too small and have little impact on the network, because each of them is only used as connection to the highway by a relatively small part of the total number of vehicles. The local roads in Santa Marta are not considered, because evacuation of the peninsula is the main goal and brings the greatest risks. It is expected that the people evacuated from the peninsula will be divided over Santa Marta and other cities outside the scope.

The capacity of the roads is based on the maximum speed, the length of the vehicle and the distance to predecessor (Bezemer, N.D.) The distance to predecessor is set to two seconds and the mean length of a vehicle is assumed to be 4.5 m, based on normal cars. To take larger vehicles, mostly buses, into account a so called pae-factor (equivalent for normal car) should be considered. A factor of 2.0 fits the best in crowded traffic situations according to Rijkswaterstaat (2017). The formula used to include the larger vehicles is stated below (Rijkswaterstaat, 2017).

$$C_{vh} = \frac{C_{pae}}{1 + (f_{pae} - 1) * \frac{a_b}{100}}$$

In this formula, the following parameters and units are used.

C_{vh}	capacity in vehicles per hour	vh/h;
C_{pae}	capacity in pae-factor per hour	pae/h;
f_{pae}	pae-factor;	[-];
a_b	share of buses	%

Under normal circumstances, a share of 20% of larger vehicles is assumed. Larger vehicles are mostly buses. Freight transport is nihil on the peninsula. During phase 2 of the evacuation process (section 2.4.3) all tourists without vehicles need to be transported, so the expectation is that more buses will be deployed in such situations. The share of buses could increase to 50%. An overview of the capacity on the highways is given in Table 2.3 and Table 2.4. The Autopista Sur and Via Blanca both have two lanes each way and the Via Rapido has a single lane both ways.

Though, it needs to be mentioned that these capacities are calculated based on Dutch standards for vehicles and road conditions, which could cause overestimation. A great share of the vehicles is not capable of reach the maximum speed due to wear and the roads in Cuba are generally in worse conditions than in The Netherlands.

Table 2.3:Capacity roads with 20% buses

Highways	Max. Speed (km/h)	Capacity (vh/h) per lane	Total capacity (one-way)
Autopista Sur	60	1320	2640
Via Blanca	100	1387	2774
Via Rapido	50	1290	1290

Table 2.4: Capacity roads with 50% buses

Highways	Max. Speed (km/h)	Capacity (vh/h) per lane	Total capacity (one-way)
Autopista Sur	60	1057	2114
Via Blanca	100	1110	2220
Via Rapido	50	1033	1033

Expected population growth

As mentioned in the introduction, tourism in Cuba is growing and will continue growing in the future. Varadero is currently responsible for 60% of the income from tourism in Cuba, thanks to its world-renowned beaches (Feinberg & Newfarmer, 2016). The growth of tourism is difficult to forecast, due to political uncertainties in Cuba. For example, whether the U.S.A and Cuba will come to an agreement or not, will determine if Americans are allowed to travel to Cuba for holidays. This could have a huge impact on the number of tourists per year (Amara, Christiansen, & Dedio, 2017). Furthermore, it is uncertain how much of an increase in visitors Cuba can handle with respect to accommodations and facilities. The Cuban government has plans to construct new hotels and resort, such as at the Oasis beach.

Because of the uncertainties three different forecast are made based on the tourism trend of the past 20 years (Figure 2.9):

- The Mintur expectation. This forecast is based on the expected growth by the Cuban Government. According to Feinberg & Newfarmer (2016) the Cuban Government is expecting over 10 million foreign visitors in 2030. This will mean that the number of tourists will increase to 22 million in 2048, based on a best fit polynomial for the number of tourists.
- The financial forecast, based on the expected contribution of travel & tourism to the Cuban GDP (Word Travel & Tourism Council, March 2018). The income from tourism will have increased by 50% by 2028. Assuming the average tourist will keep spending the same over the years the number of tourists will also be increased by 50% in 2028, resulting in a total of 15 million.
- The last forecast is solely based on a linear extrapolation of the tourism trend of the last 20 years (Salinas, Mundet, & Salinas, 2018). As opposed to the previous estimations, no projections or expectations are included in this scenario, but only the actual documented growth over the recent years has been used. This scenario results in the smallest number of tourists visiting Varadero.

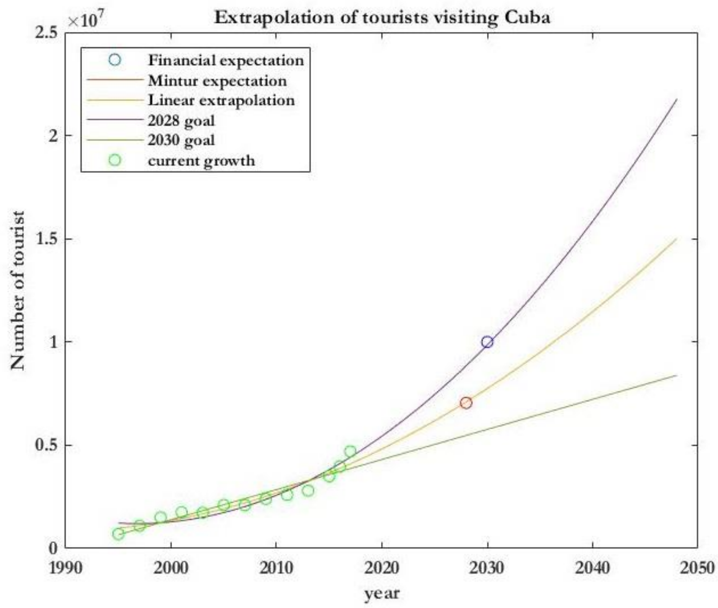


Figure 2.9: Three forecasts of tourism in Cuba

In 2017, Varadero received around 40% of all Cuba-bound tourists. This ratio is kept constant to at least 2048 in the extrapolation. Furthermore, the annual population growth factor in Cuba is currently 0.08%, this factor is used to calculate the population in 2048. The number of employees in the tourist industry of Cuba will grow by 0.7% each year (Word Travel & Tourism Council, March 2018). An overview of the trip generation in 2048 is given in Table 2.5.

Table 2.5: The expected trip generation in 2048

	Yearly	Daily	2048	Yearly		2048	Daily	
Purpose			MinTur	Financial	Linear	MinTur	Financial	Linear
Inhabitants	20,689	20,689				21,208	21,208	21,208
Work		37,000				47,000	47,000	47,000
Tourism	1,700,000	39,842	8,800,000	6,000,000	3,200,000	210,000	140,000	75,000
Total	**1,720,689**	**97,581**	**8,800,000**	**6,000,000**	**3,200,000**	**278,208**	**208,208**	**143,208**

Critical flood areas

Heavy rainfall and floods are two side effects of tropical storms and hurricanes that can provoke problems on the roads. Rainfall can cause poor visibility which impedes driving and will reduce safety on the road. The vehicles must decrease their speed and braking distances will increase. Furthermore, water on the road can cause aquaplaning, causing the vehicle to slip off the road. (Automobile Association, 2018).

As can be seen in Figure 2.8 is the highway "Autopista Sur" directly positioned next to sea, which makes the whole road very sensitive to flooding. In section 2.5.3 it is shown that hurricanes already cause high waves beforehand they make their landfall. According to the evacuation analyses (section 2.4.3) the Alert Phase, the phase wherein evacuation is required, will start 48 hours before the hurricane will strike. However, flooding must be considered while evacuating the peninsula, which can cause a reduction in the maximum evacuation time available.

Critical infrastructure areas

As mentioned in the paragraph 'Expected growth' a large increase of tourists is forecasted as well as an increase in population and employees for the coming 30 years could enlarge the probability of congestion during evacuation circumstances but also during normal circumstances.

Because the whole road is sensitive to flood, there are no certain critical areas determined based on the rainfall and floods. However, based on capacity a couple of critical areas can be determined in the transport network shown in Figure 2.10 (see Appendix D for a close-up). These are the critical areas that most likely become bottlenecks during the evacuation of the peninsula:

- Avenida Primera converges with the Autopista Sur at the end of Varadero town
- The peninsula is here connected to the mainland via Autopista Sur meaning that every vehicle needs to cross this road. Furthermore, just after the connection with mainland the highway 'Autopista Sur' turns into the Avenida Tra before becoming the Via Rapida. The two-lane road is merged into a single-lane road.

Figure 2.10: Critical areas Hicacos peninsula

2.3 Coastal Analysis

All parameters and modes of influence necessary for constructing accurate Oasis beach models will be discussed in the coastal analysis. A situation sketch of the layout will be follow by the bathymetric outline. Thereafter, granulometry is discussed to establish a good idea of the present and lacking sediment along with the relevant (current) sediment parameters. Finally, large scale oceanic influences will be discussed: currents, tidal signals, sea water temperature and sea level rise are included here.

2.3.1 General characteristics

Some constant characteristics of the Oasis beach stretch were defined earlier (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014):

- Total length of the beach in longshore direction is 800m
- The sea bed material varies between sand and rock
- The net sediment transport is directed from east to west
- Rock formations can be found at the western boundary
- The eastern boundary of the beach is the entrance of the Varadero Marina, protected by two groynes
- Between the two boundaries there are some hard structures, such as small groynes and an offshore breakwater, which do not fulfil their respective functions.

The current state of the beach at the Oasis sector can be described as minimalistic relative to the overall layout of the updrift Hicacos peninsula. Shoreline regression has been determined to average 1.2 m/y by Gamma (Cuban state engineers) and significant visual differences have been spotted compared to the previous research carried out in 2014 Figure 2.11. Tall cusps may be observed close to the eastern boundary and the layer of bedrock is exposed throughout the shallow zone of the water.

Figure 2.11: The current Beach at the Oasis sector

Data on local beach profiles and bathymetry was obtained through 49 separate measurements in august of 2017. For positions of transects P1-49 is referred to Figure 2.12. These data show that a minimal beach width of 13.2 metres can be found at P33. Furthermore, only 7 of the measured profiles are in conformity with the required beach width of 40 metres (demand B1). Six of these profiles can be found in the accretion zone east of the groyne between P10-12. Note that coastal rearrangement after demolition of the existing hydraulic structures will reduce the maximum beach width (51.9 m at P15) significantly as accretion is no longer expected to occur here.

The current state of the dune system, if present at all, is posing considerable flood risks to the hinterlands. As of august 2017, a maximum dune height of 4.2 m is observed at P19. Yet, many locations show a complete lack of dune profile. Vegetation is also sparse and will need to be actively planted to ensure dune stability following a profile nourishment. (Gamma Engineering)

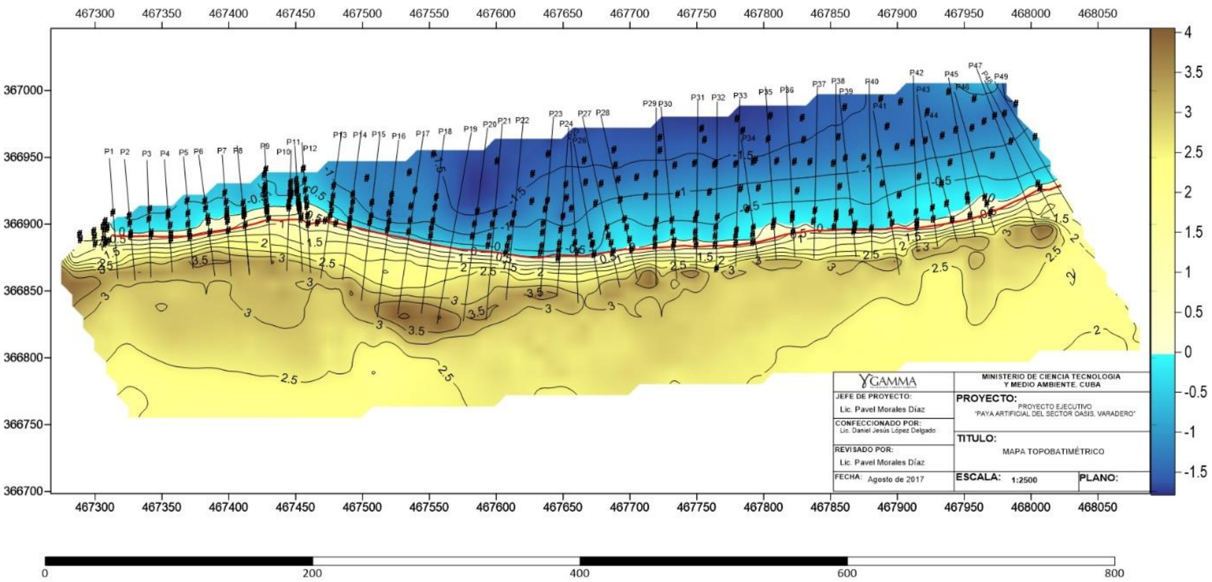


Figure 2.12: Oasis beach sediment transects

2.3.2 Bathymetry

The current nearshore bathymetry of Oasis beach is characterised by a layout of bare bedrock with sparse pockets of sediment. The bathymetry runs down from a dune height of MSL+2.5, to a beach height of approximately MSL+1.0 metre. The beach width varies along the Oasis beach, but rarely exceeds 15 metres, after which the bed level runs down from the waterline at a 1:20 slope. The Oasis sector differs from the remaining Hicacos peninsula in the shape of the foreshore. Where the wide foreshore of the peninsula provides ample space for a beach, the narrow, steep foreshore of Oasis prevents a natural beach from forming. (Gamma Engineering)

The current beach shows various signs of damage due to wave attacks. A steep profile, in which scarps and exposed bedrock are a regular sight, show the impact the waves have on the profile without protective measures.

2.3.3 Sedimentology

Section 2.5 describes the different drivers affecting sediment transport and transport gradients resulting in yearly observed coastline retreat at the Oasis beach segment. As proven by the reference projects, beach nourishment will be inevitably required as a zero-alternative. This section will deal with determining relevant parameters for sediment transport modelling: sediment diameters, grading, Chézy coefficient(s) and fall velocity.

Composition

Sediment found on Oasis beach is mainly composed of algae and carbonate sands. The share of inorganic composites however is relatively small compared to 'standard' beaches worldwide. This difference is caused by the negligible supply of terrestrial (both alluvial and aeolian) sediments. The following composition was adopted from (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014) and is thought to not have changed significantly since.

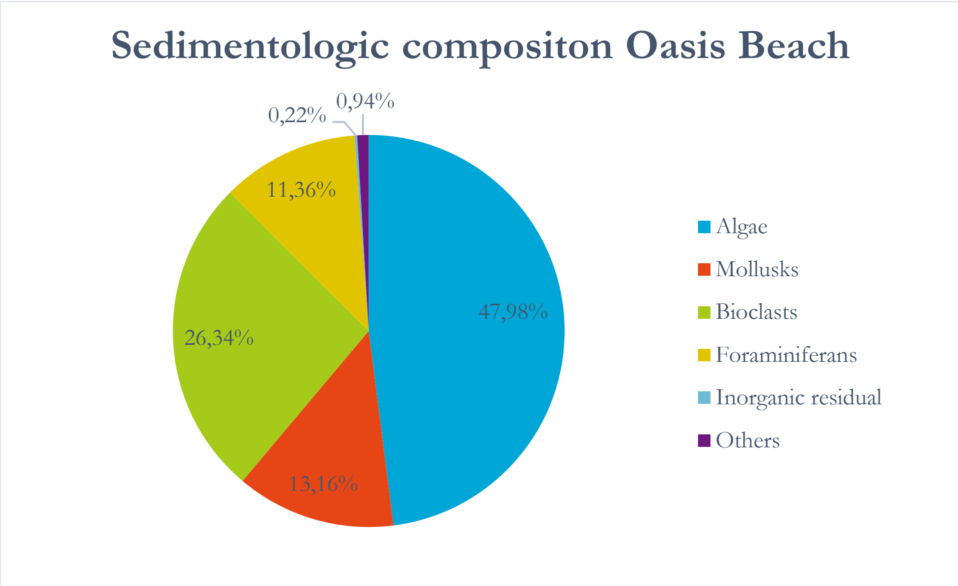


Figure 2.13: Sedimentologic composition Oasis beach, CITMA 2009

The large share of algae content stems from a field of Halimeda algae offshore of the Hicacos Peninsula. These green macroalgae are composed of green segments and are not edible to most herbivores due to their calcareous structure (van den Hoek, Mann, & Jahns, 1995). With large tropical blooms and little participation in the food chain, remains of Halimeda naturally tend to pile up. When given enough time, these stackings of so-called Halimeda sand form tropical atolls and beaches such as the ones at Varadero (Pranzini, et al., 2016).

Granulometry

For the Oasis beach segment, data on grain sizes is available for 17 out of 49 points of measurement. The series start with the first data point and proceeds to skip two data points at a time as grain sizes are not expected to differ much on such a short distance alongshore. In cross-shore sense, three samples were taken for the 17 sections. One at the dune, another at the berm and the third sample indicates the grain size of submerged sediment in case it is present. No format of cross-shore beach definitions was provided with the data. Table 2.6 depicts the layout of the Oasis beach regarding the presence of sediment.

Table 2.6: Presence of sediment in the Oasis section

Profile	Dune	Upper beach	Berm	Lower beach	Waterline	Submerged
P1	X	Sand		X	Sand	X
P4	X	Sand		X	Bedrock layer	
P7	X	Sand		X	Bedrock layer	
P10	X	Sand		X	Sand	X
P13	X	Sand		X	Bedrock layer	
P16	X	Sand		X	Sand	X
P19	X	Sand		X	Sand	X
P22	X	Sand		X	Sand	X
P25	X	Sand		X	Bedrock layer	
P28	X	Sand		X	Bedrock layer	
P31	X	Sand		X	Bedrock layer	
P34	X	Sand		X	Bedrock layer	
P37	X	Sand		X	Bedrock layer	
P40	X	Sand		X	Bedrock layer	
P43	X	Sand		X	Bedrock layer	
P46	X	Sand		X	Bedrock layer	
P49	X	Sand		X	Bedrock layer	

For each data point, the D_{10}, D_{50} and D_{90} were determined. Subsequently, each transect delivered an average value for these respective diameters. Results for these averages and their overall mean value are plotted in Figure 2.14 below. (Gamma Engineering)

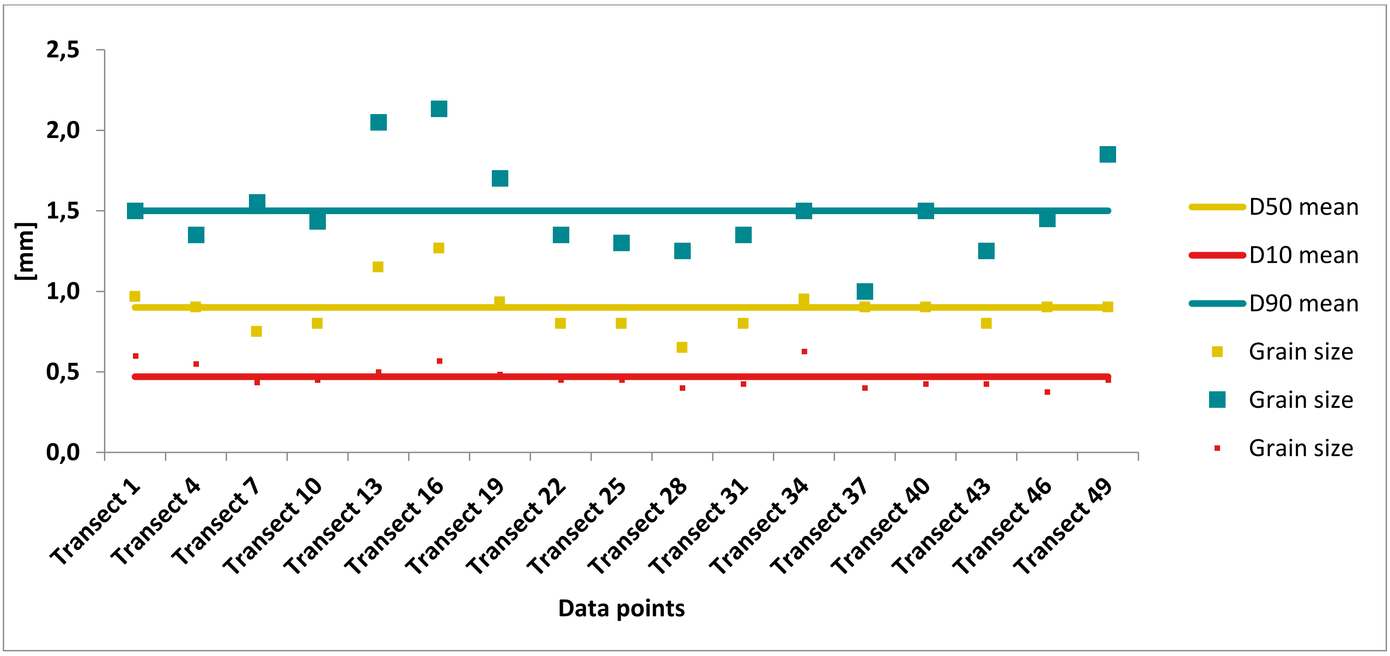


Figure 2.14: Average of values of transect for diameters D10, D50 and D90

As can be concluded from Figure 2.14, the D_{90} is roughly three times larger than the D_{10}. According to (Bosboom & Stive, 2015) we can speak of a well-graded (or poorly sorted) sand indicating a wide range in available grainsizes. The implications of such a grading are a relatively large heterogeneity in sediment response to different hydrodynamics.

An observed median grainsize value of 0.90 mm indicates the presence of medium-sized sediment in the Unified Soils Classification. Another classification by Wentworth defines the phi-value:

$$\phi = -\log_2 D$$

Which results in $\phi = 0.15$ in this case, leading to a classification as coarse sand. A rule of thumb is that medium-sized sand particles have fall velocities ranging from 0.01 to 0.05 m/s. It is to be expected that a fall velocity of over 0.05 m/s is found. (Bosboom & Stive, 2015)

The borrowing area for sand nourishments executed in Varadero has traditionally been south of Cayo Mono (Monkey Key). A mean sand diameter of 0.38 mm could be found here per 2001 and the sediment classification ranges from fine to coarse (up to 0.66 mm) (Kaput, Koenis, Nooij, Sikkema, & van der Wardt, 2007). An updated granulometry was not provided but the old chart is said to be representative for grainsizes found today as well.

Sand of similar grainsize and grading as the original beach needs to be applied for the successful execution of nourishments. Somewhat coarser sediment can also be applied to slow down diminishment of the added sand. However, the creation of a beach with visual characteristics comparable to the beaches on Peninsula de Hicacos is prioritised. The finer grading of Cayo Mono sand implies positive aesthetical qualities for the nourished Oasis beach though more margin needs to be taken on the nourishment volume due to large washout.

Grainsize associated parameters

The available data on granulometry allows for the computation of two important model input parameters: the Chézy coefficient and fall velocity of sediment.

The calculation for the Chézy coefficient was partly adopted from (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014). However, the coefficient is indirectly dependent on climate conditions. As can be seen in the formula, the Chézy value depends on the local water depth (h). Although this value fluctuates in storm conditions due storm surge and wind, a constant water depth of 0.6 meter is assumed as a first estimation. At this water depth the first waves during normal conditions start breaking. The roughness height is set at 1.5 mm, which is equal to 3 times the local D90. This results in a Chézy coefficient of 66.3 $m^{1/2}\ s^{-1}$.

$$C = 18 \log\left(\frac{12h}{r}\right) 66.3$$

C	Chézy coefficient during either normal, cold front or storm conditions	$m^{1/2}\ s^{-1}$;
h	Depth at breaking of first wave	m;
r	Roughness height	m

An important parameter that governs the behaviour of sediments in the near-coast is the fall velocity. This value will be used in all models to come. The fall velocity can be found as follows:

$$w_s = \sqrt{\frac{4}{3} * \frac{gD_{50}}{C_D}\left[\frac{\rho_s}{\rho_w} - 1\right]}$$

g	gravitational acceleration	9.81	m/s^2;	
ϱ_s	sediment density	2700	kg/m^3;	
ϱ_w	water density	1022	kg/m^3;	*
D_{50}	median grain diameter	0.90	mm;	
C_D	drag coefficient	t.b.d.	[-]	

The drag coefficient (C_D) depends on the grain Reynolds number defined as:

$$Re = \frac{w_s D}{\nu}$$

ν	kinematic viscosity	0.866e-6	m^2/s;	*
D	representative particle diameter	0.90	mm	

The grain Reynolds number itself depends on the fall velocity (w_s) hence, iterative computation of this parameter was required. The iteration can also be found in the Shields parameter diagram (Bosboom & Stive, 2015):

Re	grain Reynolds number	116	[-]

Low magnitude ($<10^{-1}$) Reynolds numbers indicate drag conditions in the Stokes-range. For more turbulent conditions (>400) the regime is said to be in the Newton-range. The transition range between these two distinct regimes call for either a numerical (e.g. CRESS) or analytical solution (charts, tables). Here, the latter was chosen and both the drag coefficient and fall velocity were determined.

C_D	drag coefficient	0.95	[-];
w_s	fall velocity	0.11	m/s

This value of 0.11 m/s is slightly larger than the default input value of 0.10 m/s for the settling velocity in most models.
* (Dekker, Leijnse, Simonse, & van Westen, 2017)

2.3.4 Oceanology

Currents

The magnitudes and directions of currents along Oasis beach are governed by a combination of wind and tidal influences. The dominant angle of wave incidence and its consequent refraction pattern cause lower wave set-up in western direction along the wave crests. Hence, the dominant alongshore current is directed from east to west.

On a larger scale, the Gulfstream dictates the flow regime in the Florida Strait (Figure 2.15). This current originates from the southern Atlantic Ocean and is orientated from west to east causing the flood tidal current to flow in east-north-eastern direction. The ebb tidal current is directed in west-south-western direction. The tidal velocities average 0.10 m/s with a maximum of 0.37 m/s (Dekker, Leijnse, Simonse, & van Westen, 2017).

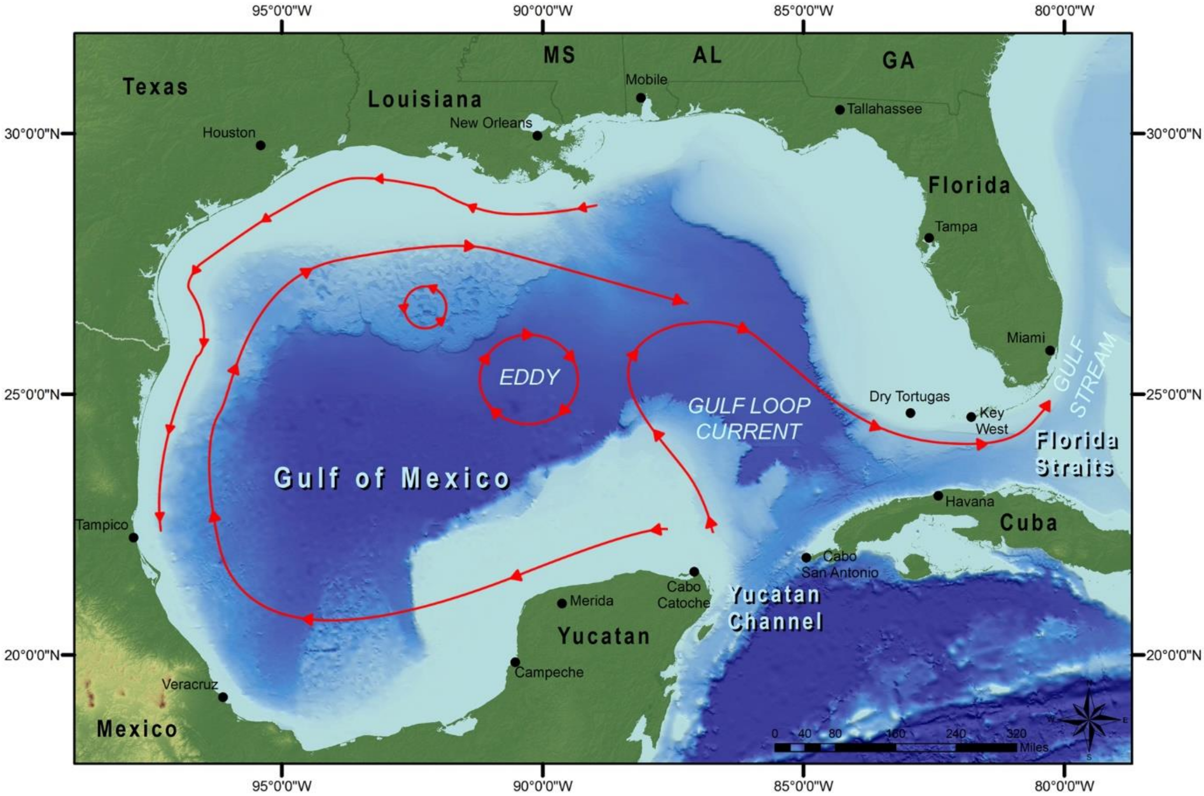


Figure 2.15: The flow regime in the Florida Strait

Tide

Varadero is bordered by the Florida Strait and Gulf of Mexico. Both approach characteristics of enclosed seas, hence the mean spring tidal range is small at around 0.7 m. The tidal range in normal conditions is around 0.4 m with a maximum of 0.7 m (Table 2.7). Tidal observation station Havana IHO supplied the following tidal constituents relevant for the Varadero coast.

Table 2.7: The tidal observations (Bosboom & Stive, 2015)

Tidal signal		Amplitude [m]	Tidal cycle [d]	Tidal period [h]
M2		0.127	28.986	12.42
O1		0.101	13.943	25.82
K1		0.094	15.044	23.93
S2		0.042	30.000	12.00
P1		0.026	14.956	24.07
N2		0.026	28.436	12.66
Q1		0.023	13.398	26.87
K2		0.012	30.075	11.97
M4		0.004	57.968	6.21

A joint influence of diurnal and semi-diurnal components can be observed. The influence of higher harmonics is minimal. The form factor (F) can be used to assess the qualitative influence of diurnal and semi-diurnal components on the tidal signal:

$$F = \frac{K_1 + O_1}{M2 + S2} = 1.15$$

K1	Lunar-solar declinational amplitude	m;
O1	Principal lunar diurnal amplitude	m;
M2	Principal lunar semidiurnal amplitude	m;
S2	Principal solar semidiurnal amplitude	m

Four distinctions can then be made according to (Bosboom & Stive, 2015) (Table 2.8)

Table 2.8: The four distinctions of diurnal and semi-diurnal components

Category	Form factor (F)
Semidiurnal	0 – 0.25
Mixed – semidiurnal dominance	0.25 – 1.5
Mixed – diurnal dominance	1.5 – 3
Diurnal	> 3

Thus, the Varadero tidal climate is characterised as mixed with a dominance of semidiurnal signals and a relatively small tidal range. The tidal signal is given by the following series:

$$\eta(t) = a_0 + \sum_{n=1}^{N} a_n \cos(\omega_n t - \alpha_n)$$

$\eta(t)$	predicted tidal level relative to origin of the z-axis	m;
a_0	mean water level	m;
a_n	amplitude of tidal component n	m;
ω_n	angular velocity of tidal component n	hr^{-1};
α_n	phase angle of component number n	[-];
t	point in time	hr;
N	number of tidal components	[-]

The tidal signal has been visualised over a period of one month using Python programming software and can be seen in Figure 2.16. A mixed tidal character can be deduced from this figure. The tide shows its semidiurnal quality in the two distinct oscillations per day, but the tidal amplitude differs greatly between the two oscillations, which shows the large influence of the diurnal components. The figure concerns the rare scenario of complete phase alignment of all tidal components at t=0, resulting in the maximum amplitude of the tidal signal. Note that this maximum tidal range is still relatively small at 0.7 m.

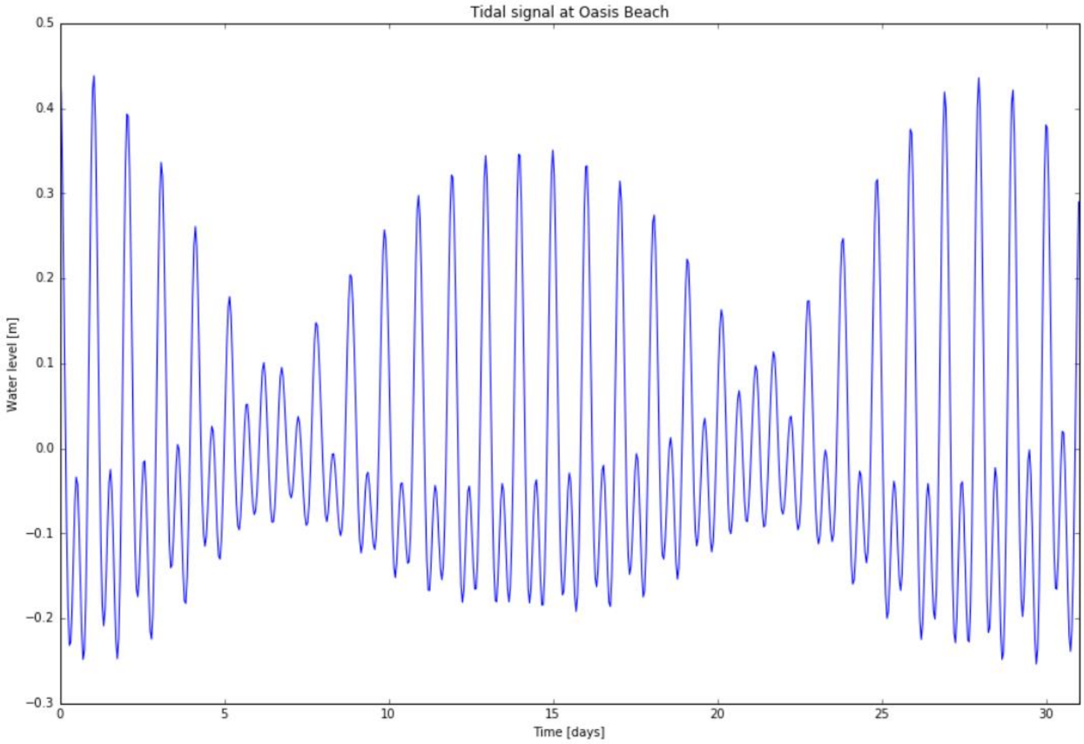


Figure 2.16: Monthly signals

Temperature variations

Temperature variations of the local nearshore are relevant to map for the biotechnological solution, which will be discussed in Section 3.3.2. Habitation of marine zones is heavily influenced by the water temperature.

The monthly range of seawater temperatures has an average width of 6 °C Figure 2.17 (Dekker, Leijnse, Simonse, & van Westen, 2017). Shallow surface waters in the wake of engineered structures are expected to average 25 °C year-round.

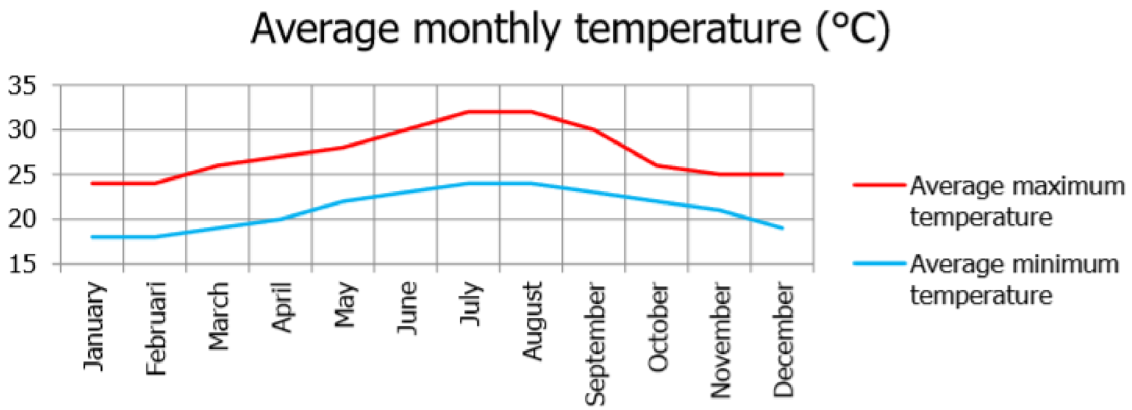


Figure 2.17: Monthly range of seawater temperature

Sea level rise

A scientific consensus exists regarding the acceleration of global sea level rise (IPCC, 2017). Though its averaged magnitude is very uncertain and dependent on many parameters. Also, a variety of values for sea level rise (acceleration) were reported in the Varadero reference projects.

Short reinvestigation of this matter resulted, rather surprisingly, in no significant fluctuations of the mean water level for the Varadero coastal zone (IPCC, 2017). The key principle here is the uneven distribution of sea level rise globally. Also, for monitoring of flood safety, one must address relative sea level rise rather than absolute sea level rise. The difference being the consideration of local land subsidence. As both sea level rise and land subsidence in Varadero are zero, sea level rise is not included in the modelling phase.

The north Matanzas coast is situated at the border of two zones that will experience (absolute) sea level decrease (eastern Caribbean) and rise (south coast US) respectively. Hence, it experiences an insignificant amount of sea level rise acceleration Current sea level rise predictions will persist though and some local subsidence may be attributed to oil and groundwater extractions, but this is not considered in the project scope.

2.4 Wind conditions

This section describes the three types of wind conditions, which cause various wave climates on the Oasis beach sector. These conditions will be used to determine and model the wave attack on Oasis beach.

2.4.1 Regular conditions

The Cuban climate is tempered by the year-round presence of the tropical easterly coming from the northeast. This uniformity in wind direction can also be observed locally in Varadero as depicted by the wind rose below.

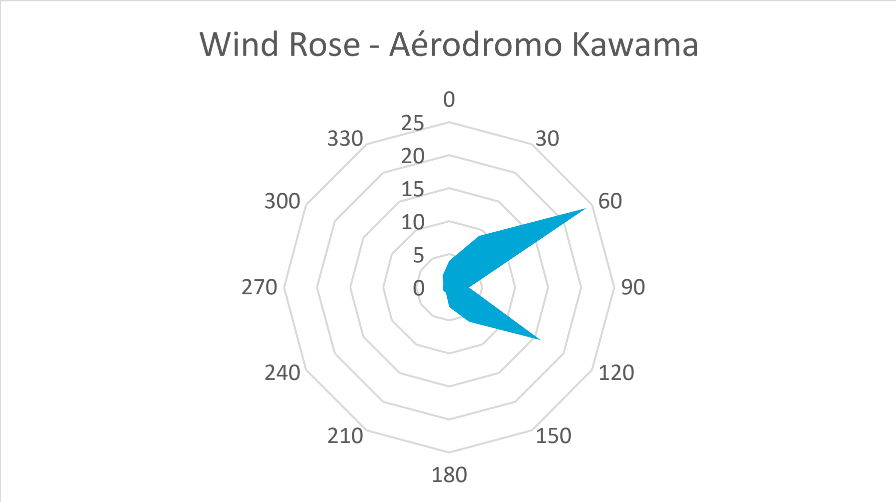


Figure 2.18: Wind rose of Varadero

Also, the associated windspeeds are characterised by a narrow spectrum due to the homogeneous nature of the trade winds. The weekly-averaged windspeeds for Varadero reach 6.4 m/s without exceptions during the year. This will obviously not hold during cold front and hurricane conditions. It is also to be noted that the observed windspeed (just as the direction) is valid for the on-land weather station at Aeródromo Kawama airport.

2.4.2 Cold front conditions

The phenomenon known as a cold front arises when cold and dry high-altitude air passes over hot and humid low-altitude air. Cuba experiences these cold fronts regularly during the dry-season (Dec-Mar, see section 1.1). Cold fronts force a change in weather conditions, initiating hard winds from the northwest accompanied by rainfall and more erratic conditions at sea.

Especially this change in wind-direction is important as wave incidence in Varadero will change from a northeast to a northwest originated wave climate, implying a reversal of sediment transport direction in alongshore sense.

Cold fronts in Varadero are characterised as follows (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014);

Table 2.9: Cold front characteristics

Direction	φ	315˚ (NW)
Mean duration	$T_{m,cf}$	18 h
Mean frequency	$f_{m,cf}$	21 y^{-1}
Max. frequency [1]	$f_{max,cf}$	36 y^{-1}
Significant wave height	$H_{s,cf}$	~2 m
Peak wave period	$T_{p,cf}$	~8 s
Wind speed categories		Weak: <10 m/s Moderate: 10 – 15 m/s Strong: >15 m/s

The above mean values of duration and frequency indicate a presence of cold front conditions for 15.75 days in an average year. When looking at the maximum occurrence measured by the Cuban meteorological institute in the last 60 years, cold fronts could occupy up to 27 days in a year. These approximations will be used in modelling cross-shore responses of Oasis beach during cold front events.

The relatively long duration of altered wind conditions is also expressed in the yearly offshore wave climate depicted in Figure 2.19. The wave height is indicated by the values on the ring.

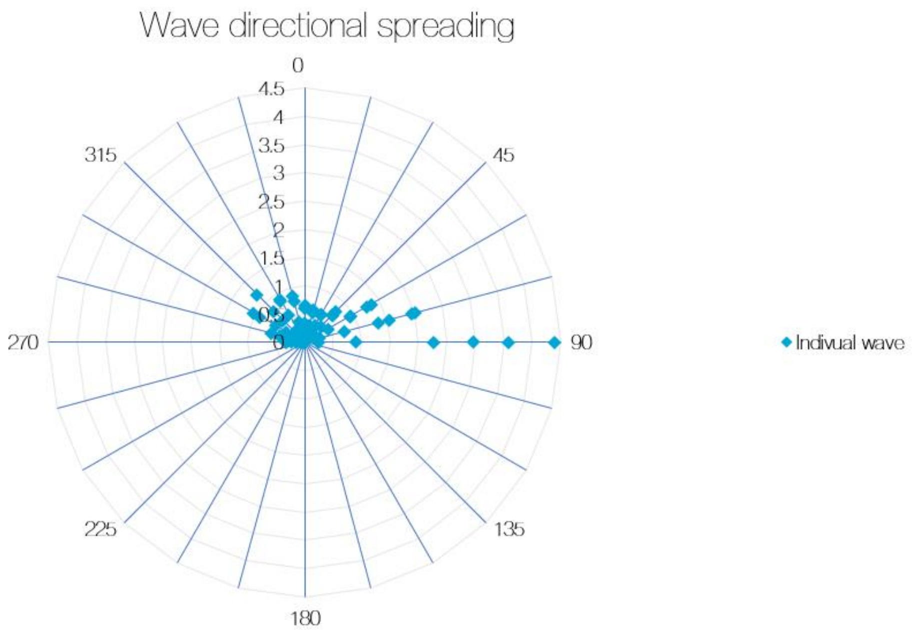


Figure 2.19: Yearly offshore wave spreading

[1] (Dekker, Leijnse, Simonse, & van Westen, 2017)

2.4.3 Hurricane conditions

Tropical depressions are documented per storm season. When tropical depressions develop into tropical storms and exceed threshold windspeeds of 119 km/h, we speak of hurricane conditions. The normative design conditions for a hurricane will be determined in section 2.5.

The strength of a hurricane is defined by the range of observed windspeeds at its periphery and the (low) air pressure at its centre. The level of classification does not fully cover the impact of a hurricane though. Its interaction with other climatic factors and trajectory are mainly responsible for its destructive nature. Five classes of hurricanes are distinguished on the Saffir-Simpson scale (Table 2.10.)

Table 2.10: Hurricane categories on the Saffir-Simpson scale

Category	Windspeed range (km/h)	Central air pressure (hPa)	Implications*
1	119-153	> 980	Dangerous winds
2	154-177	979 – 965	Extensive damage
3	178-209	964 – 945	Devastating damage
4	210-250	944 – 920	Catastrophic
5	Over 250	< 920	Cataclysmic

* Consult Appendix E for a more detailed indication of damages per hurricane category

Hurricane formation

As has been described in section 1.1, the island of Cuba is prone to extreme storm conditions. The most infamous example of this being the hurricane which is a low-pressure system known to form on the Atlantic Ocean. Apart from tremendous wind speeds, this phenomenon is associated with extensive rainfall, water level elevations and electrical effects.

The formation of hurricanes was not accurately described before the 1960s (Charney & Eliassen, 1964). Innovations particularly in the field of remote sensing brought new and well-founded insights in the processes that steer the formation, persistence and dissipation of tropical cyclones.

Hurricanes find their origin in tropical disturbances, these are asymmetrical low-pressure zones found in tropical areas. About one hundred of these disturbances are reported yearly. Tropical disturbances themselves are rooted from tropical waves which are elongated zones of relatively low air pressure. When the ever-present easterly trade winds push the tropical wave westwards, convection patterns start to occur. The first signs of rotational movement start to occur in this stage and when a closed surface circulation is observed we speak of a tropical depression.

Tropical depressions can gain in strength enormously if fuelled enough by warm and moist air on the equatorial waters. The upward movement of this moisture will cause it to gradually cool down and latent heat is released back into the air. This heat is subsequently available to energise more cold air. All this rising air causes a short-term pressure gradient and is hence quickly replaced by the surrounding atmosphere. The latter phenomenon is responsible for the winds associated with depressions. Whenever a tropical depression organises itself by showing a distinct low-pressure eye and geometrically stable spiralling movement we speak of a tropical storm. Roughly half of all tropical storms proceed to become hurricanes, though many will never reach land and dissipate swiftly.

When windspeeds in tropical storms start exceeding 119 km/h we observe a highly organised spiralling pattern of high windspeeds at the eyewall and calm conditions in the low-pressure eye.

These are hurricane conditions. As soon as a hurricane makes landfall, its strength will start a sharp decrease in the absence of sufficient amounts of warm moisture (Cangialosi & Berg, 2012).

Evidently, the process scheme as described above is a severe simplification of hurricane formation. Upper ocean heat content, topographical interaction, vertical wind shear and eyewall replacement cycles are amongst other factors that heavily influence the way in which a hurricane is formed.

Trajectories and lifecycle

Accurate records of hurricane intensities and trajectories date back to the late 19th century. This long running data series provides helpful insights in forecasting and emergency measures for governments affected by these destructive events. For the Cuban government this is an especially valid statement as the island is positioned in between every annually recurring hurricane pathway. An infamous example of these pathways is formed in the so-called Cape Verde season. This season is named after the African island nation close to the breeding ground of these hurricanes and spans from August to November. It has distinct probability peaks in September and October as can be seen in Figure 2.20 (Cangialosi & Berg, 2012). Furthermore, locally generated (Gulf of Mexico) hurricanes affect Cuba outside and inside the Cape Verde season.

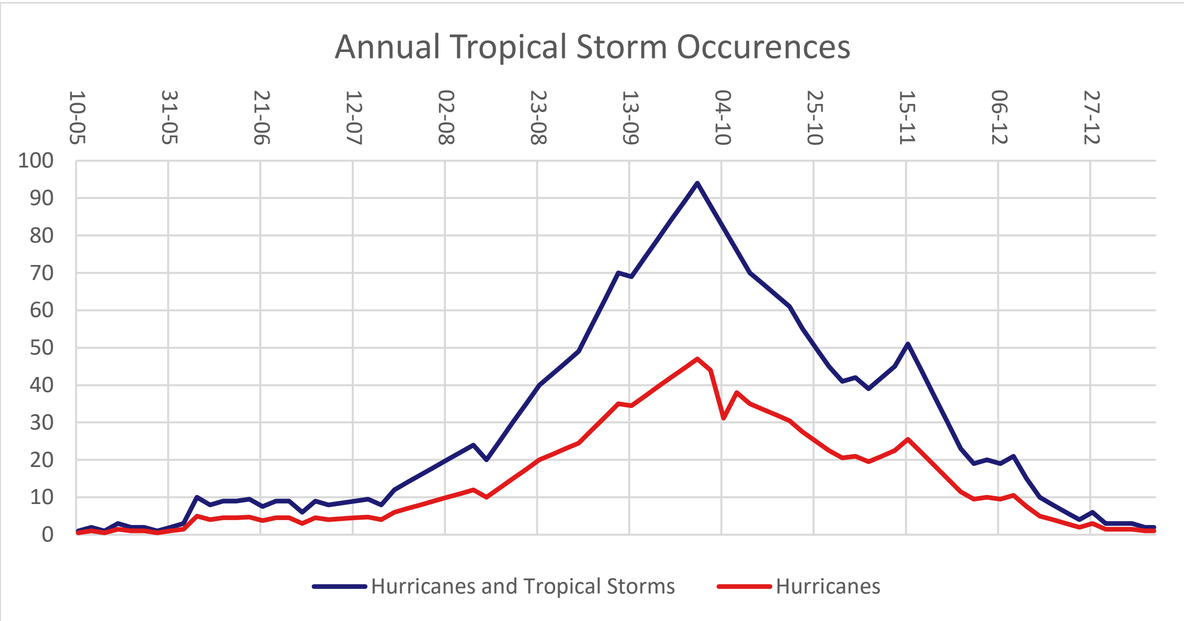


Figure 2.20: Number of tropical storm occurrences vs. time in year per 100 years in the Caribbean ((Cangialosi, Latto, & Berg, June 2018))

As described in the previous section, the trajectories of hurricanes can largely determine its destructive potential. Another important factor is the duration in which the storm can be called a tropical cyclone. This lifetime segment is related to the most forceful windspeeds, a typical timeline of a Cape Verde hurricane can be seen in

Table 2.11. (Cangialosi & Berg, 2012).

Table 2.11:General path of hurricanes developing in Atlantic basin

Time (d)	**Location** (dynamic)	**Status**
$t = t_0$	Cape Verde	Tropical normal conditions
$0 < t < 5$	Central Atlantic Ocean	Tropical disturbance
$5 < t < 6$	Western Atlantic Ocean	Tropical depression
$6 < t < 9$	Eastern Caribbean	Tropical storm
$9 < t < 15$	Caribbean and coastal US	Hurricane
$15 < t < 17$	North-eastern US and Canada	Extratropical transition
$t > 17$	Northern Atlantic Ocean	Extratropical cyclone

As can be seen in Table 2.12, Cuba deals with a three-yearly recurrence pattern for hurricane events on average. It must be noted that these statistics apply to the whole of the approximately 1000 km wide island. The more destructive hurricanes affecting Cuba usually pass its eastern coast, a fair distance away from the Oasis beach project site. These events do however carry the possibility of affecting cross-shore sediment processes along the coastal periphery of Cuba. In section 2.5.3, a design condition for hurricane conditions is determined.

Table 2.12:Estimation of hurricane frequencies

Category	Frequency (y^{-1})	Return period (y)
1	0.34	3
2	0.23	4
3	0.12	8
4	0.08	13
5	0	0

(Dekker, Leijnse, Simonse, & van Westen, 2017)

The latest significant events and their impact have been tabulated in Table 2.13 (European Commission, 2018). It can be concluded that 2017 marked an extreme year relative to e.g. 2013-2014. Maria, Irma and Harvey each caused enormous damages to life and property. The disproportionally large loss of life caused by hurricane Matthew in 2016 can be traced back to its trajectory over Haiti that was struck by a catastrophic earthquake of 7.0 on the Richter scale in 2010 and had not recovered from this event since. (NOS, 2010)

Table 2.13: Recent history of Caribbean hurricanes (2012-2017)

Year	Name	Duration[d]	Category	Max. U_{wind} [km/h]	Fatalities	Economic loss [M€]	Affected Cuba [Y/N]
2017	Maria	15	5	280	146	78,000	N
	Irma	14	5	265	52	42,000	Y
	Harvey	16	4	215	68	107,000	N
2016	Earl	5	1	140	106	214	N
	Matthew	12	5	270	586	8,000	Y
2015	Erika	5	Tropical storm	85	31	436	N
	Joaquin	11	4	250	34	171	Y
2013	Ingrid	6	1	140	23	1,000	N
2012	Isaac	11	1	130	34	201	Y
	Sandy	8	3	185	147	56,000	Y

(European Comission, Joint Research Centre, 2018)

Hurricane example: Wilma (2005)

Tropical depression 24 in 2005 may not sound familiar to many. However, the thrashing power of hurricane Wilma will be known by many, as it was the most powerful hurricane to ever make land. When looking at the trajectory of Wilma in Figure 2.21, a typical late-season hurricane trajectory (National Hurrican Center, 2018)

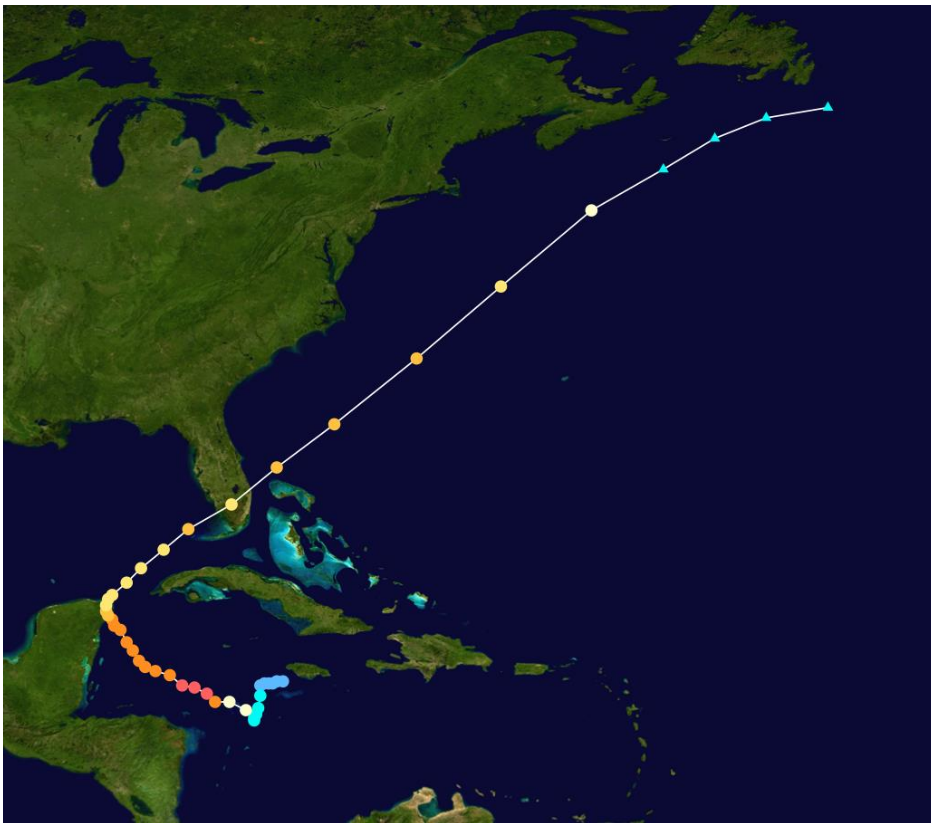


Figure 2.21: Path of hurricane Wilma (2005)

Wilma retained a status as tropical depression in Montego Bay, Jamaica before rapidly growing to a category 5 hurricane on early October 19th. Colour gradients indicate placement on the Saffir-Simpson scale (Table 2.13).

A record-holding windspeed of 311 km/h was measured by a reconnaissance airplane and the resulting eye width and eye air pressure (884 hPa) are values that have not been observed ever since. The same night, Wilma had stabilised to be a hurricane of category 4 and started a trajectory in north-eastern direction. The effect of this part of its trajectory on the Oasis beach was modelled (section 3.2) as this part of the trajectory passed no less than 135 km off the coast (Roses, 2018).

Some important statistics relevant for Cuba and the project site in specific are listed below:

- Zero direct Cuban fatalities due to effective evacuation (People's World, 2005)
- Highest recorded persistent windspeed of 280 km/h (Roses, 2018)
- Period of influence on Cuba of 4 days (National Hurrican Center, 2018)
- Associated offshore H_s of up to 7.3 metres (Section 2.5.3)

Hurricane example: Irma (2017)

Sustained windspeeds like those in Wilma (2005) were not measured until the ninth tropical depression of 2017. The Cape Verde depression developed into hurricane Irma on august 31st that year. Its long lifetime (14 days, Table 2.13) caused it to become second in inflicted economic damage after Maria that same year. Considering the project scope, hurricane Irma is of prime interest to the research given its trajectory and intensity (Cat 5, Table 2.13) when it made landfall on Cuba. Some relevant characteristics involve:

- Ten direct Cuban fatalities (Sullivan, 2017)
- Destruction of 210.000 homes and damage to tourist facilities (Sullivan, 2017)
- Trajectory included passage near (< 50 km) Oasis Beach (European Commission, 2018)
- Highest recorded persistent windspeed of 285 km/h (Table 2.13)
- Period of influence on Varadero of 3 days (section 2.5.3)
- Associated offshore H_s of up to 9.4 metres (section 2.5.3)

Hurricane Irma showed the distinct characteristics of a Cape Verde system coming from the eastern Atlantic Ocean where it moved westward and quickly progressed through the categories of the Saffir-Simpson scale. The so-called maximum danger trajectory as achieved between September 8th and 10th while moving along the north-eastern to north central coast of Cuba (Roses, 2018). The exact trajectory and associated windspeeds can be seen in Figure 2.22: Path of hurricane Irma (2017). Irma made a sharp turn towards Florida just 45 kilometres northeast of Peninsula de Hicacos. Multiple inundations of the hotel area were subsequently reported.

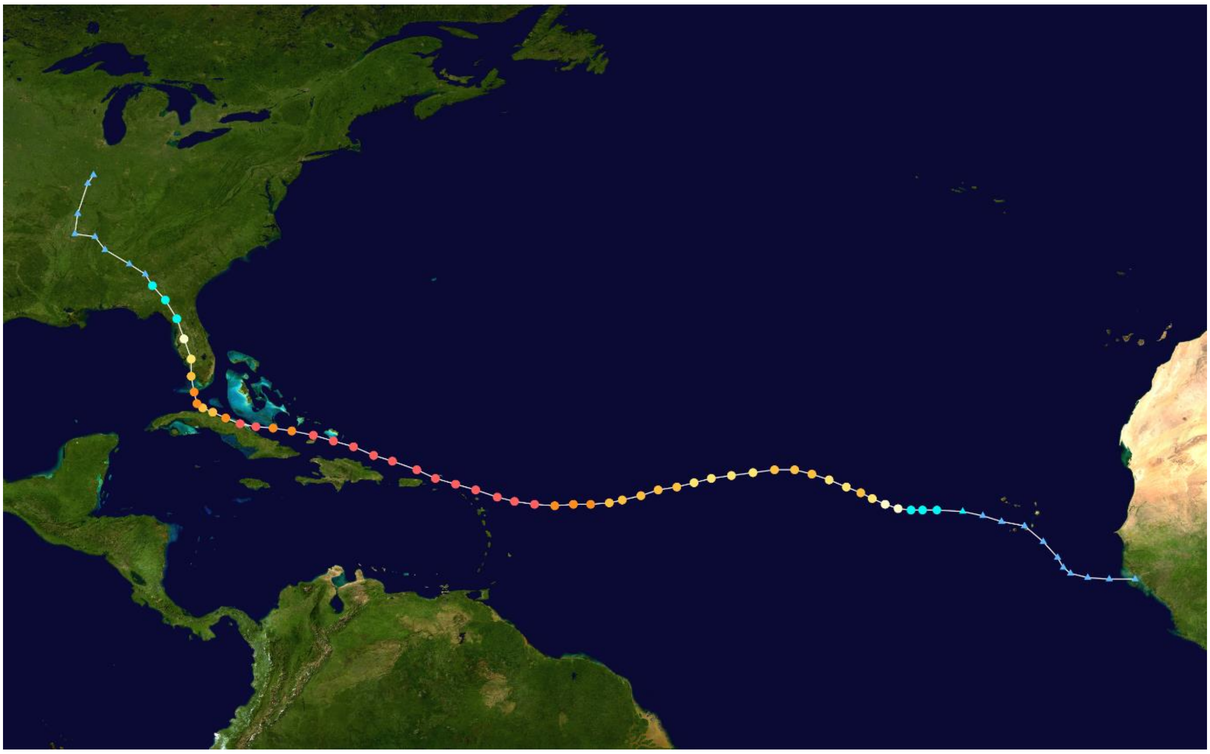


Figure 2.22: Path of hurricane Irma (2017)

Emergency planning

Cuban preparation and evacuation in hurricane events functions famously well. On average, less fatalities are reported for equal storm conditions relative to neighbouring states (Wisner, 2001). During hurricane Wilma, more than 760.000 people were evacuated. Over 500.000 took shelter in homes of family or neighbours and the rest in previously prepared shelters (Havana Journal, 2005). Before Hurricane Irma made landfall nearly one million people were evacuated including many tourists. The measures went as far as the evacuation of dolphins from the nearshore cayos.

The small number of casualties inflicted by hurricanes compared to other Caribbean countries has several reasons. Firstly, Cuba has a well-educated population that is trained for dealing with such natural disasters and Cuban housing is well-prepared in general (Pichler & Striessnig, 2013). Secondly and more importantly, the Cuban disaster management, which is strengthened by the Cuban socialist structure. In case of emergencies, the government relies on neighbourhood-based organizations which are responsible for mobilizing labour, developing preparedness and guaranteeing cooperation among citizens but also between authorities.

The participation of the Cuban population is a critical element in the disaster reduction plan (Pichler & Striessnig, 2013). Furthermore, trust in the government is another critical element:

> "Trust is the key in getting people to utilize lifeline structures during times of emergency."
>
> \- (Sims & Vogelmann, 2002)

Citizens must have confidence in the system and its necessary recourse functions to work on reducing their own risk. Recourses are for example emergency warning systems, available shelters and medical services. Trust is gained through education and community organization and social capital. From elementary school on, disaster preparedness and response are part of the curriculum.

Furthermore, risk reduction trainings are given in institutions and workplaces (Sims & Vogelmann, 2002) (Pichler & Striessnig, 2013).

Following the Institute of Meteorology, a unit of the Ministry of Science, Technology and Environment informs the government about upcoming events. The government then decides whether the disaster reduction plan must be implemented or not. However, due to the isolation of Cuba the last 50 years, the institute has limited funds and the equipment is outdated, which creates difficulties in forecasting weather conditions. For example, last year the Cuban meteorologists did not identify the threat posed to the island by Hurricane Irma early on. Fuel conservation regulations were issued in the Camagüey province in case of post-storm black-outs. When the extent of the storm system became apparent, evacuation was immediately set in motion. Fortunately, despite political conflicts, the Cuban Meteorology Centre in Havana and the US National Hurricane Centre in Miami still share their data and communications. So, hurricane preparedness can be enhanced due to information exchange (Thompson, 2007)

If the government decides the emergency plan must be implemented, will this be done by the High Command of the National Civil Defence which directs the national civil defence and the Red Cross. The national plan consists of four-phases, the instructions for the phases are taught in schools and workplaces. (Thompson, 2007) (Miranda & Choonara, 2011) (Sims & Vogelmann, 2002) The phases are:

1. The Emergency phase. 72 hours before a hurricane is expected to hit, the media begins to inform the population via intensive coverage. The Civil Defence structure is put on alert, this organization consists of the heads of provincial and municipal assemblies as well as local heads of the Civil Defence. These heads of Defence activate their structures and organize their command centres, assign transport and equipment where needed and review their emergency plans. The same accounts at communication level, school directors, head of workplaces and family doctors, making sure their list of vulnerable people and plans are up to date.
2. The Alert phase. The National Civil Defence command centres become the location of all coordination and information and every goes in full mobilization. When the High Command of the National Civil Defence orders that evacuation needs to start, all evacuation of high risk populations begins. Evacuating is ordered 48 hours before the Hurricane is estimated to make landfall according to the Meteorological institute. Whenever a family lives in a house that is certified as safe and is not in a flood zone, it can decide to stay and take in neighbours from non-certified houses. If a family lives in a house with a roof of tile, thatch or fibre-cement, they will be assigned to move to a house certified as safe. In case all nearby houses have already been assigned and there is no place at relatives or friends, the family will be put in a group shelter and transport is provided. These shelters are set up in community buildings or schools, they receive water, supplies and medicines. Each shelter has a director, a deputy, a doctor, a nurse, a psychologist, a veterinarian for pets, police and a representative of the Red Cross.
3. The Alarm phase. The hurricane strikes, and this phase will last until the hurricane has passed the area. All Civil Defence workers must stay at their posts and keep in communication with the central structure. The media broadcasts information and everyone must stay indoors.

4. The Recovery phase. The storm has left the country and the Civil Defence heads must mobilize teams for clean-up, repair of electricity lines, provision of safe drinking water. The National Civil Defence needs to certify that homes are safe first before people can return to them. Economic losses, housing damage and agricultural losses will be calculated. The phase will last until areas are cleaned up and services are restored.

When the High Command of the National Civil Defence determines that the emergency system can be deactivated, he will propose it to the President. Only if the Presidents approves the deactivation will the country return to its normal governance procedures and decision-making.

2.5 Wave conditions analysis

The Oasis beach is subject to various conditions. As described in section 2.4, the three condition types are the normal wave conditions, cold front conditions and the occurrence of a hurricane. To determine these conditions, ARGOSS wave data is used. (ARGOSS, 2018)

Firstly, the significant wave height, peak period and direction have been downloaded from the ARGOSS database, using the boundaries shown in Figure 2.23. Note that the data gathered are deep water data points based on model output. The availability of LIDAR samples is limited in the area, which results in small datasets, which either do not represent the conditions properly, or are not shown at all by ARGOSS as they are not considered dependable.

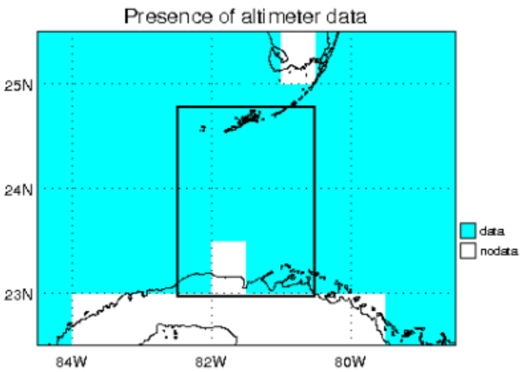


Figure 2.23: ARGOSS boundaries

2.5.1 Normal conditions

The normal wave conditions of Oasis beach are defined as the mean significant wave height of all waves in the ARGOSS spectral parameters. The corresponding direction is determined using the same method. The corresponding peak period is found by referencing the table in which the peak periods are distributed over wave height and wave direction. The following table shows the resulting normal conditions.

Table 2.14: Normal wave conditions

Parameter	Value
Hs	0.513 [m]
Tp	4.32 [s]
Dir	67.9 [°]

2.5.2 Cold front conditions

As stated in section 2.4.2, cold fronts on average occur 16 days per year. During cold fronts, waves are known to come from the northwest. From the ARGOSS data, waves with an angle of incidence of 277.5 to 352.5 are considered for this situation. A large spread in significant wave heights can be observed) between 0.2 and 2.4 metres, not even including some outliers where the significant wave height reaches almost 4.0 metres, as these measurements are likely to have been caused by storm waves from a hurricane, as a frequent hurricane path lies in this zone. A significant wave height of 2.1 metres is chosen as a best estimate. These waves are not considered for the cold front conditions. (ARGOSS, 2018)

Based again on the available ARGOSS data, an average peak period corresponding to the normative waves in cold front conditions of 7.67 seconds is found. The following parameters are thus used to characterise a storm front.

Table 2.15: Cold front wave conditions

Parameter	Value
H_s	2.1 [m]
T_p	7.67 [s]
Dir	315 [°]

2.5.3 Hurricane conditions

As defined in our list of demands in section 1.6 the beach must withstand a 1-in-10-year hurricane (demand S1.2). As hurricanes are responsible for the most severe wave conditions, this storm can be quantified by determining the 1-in-10-year wave conditions.

The model output from the ARGOSS data is composed of 75,982 values for the significant wave height, which have been sampled between 1999 and 2017. This means that the average sampling time is approximately two hours. A precision of 0.5 metre is given in the Distribution of wave heights in bins. Using extreme value theory, it is possible to extrapolate from this data to a design value for any lifetime required. Note that due to the lack of a measured time-series of wave heights, the timeseries has been created by assigning the maximum significant wave height to all samples in a wave height bin. For large lifetimes (larger than the sampling period of 18 years) the precision of this estimate is poor, but for the required period of ten years it is expected to be sufficient. The quality of the estimate will be expressed using a ninety percent confidence interval. (ARGOSS, 2018)

Significant wave height

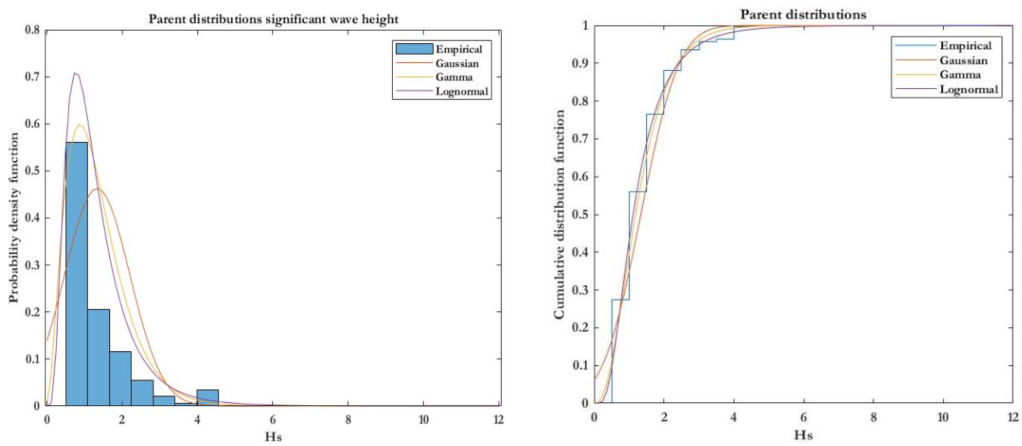
To extrapolate from the dataset, a statistical distribution which fits the data must be chosen. The most common extreme value distributions are Gumbel, Fréchet and inverse Weibull. To test the relative accuracy of these distributions, they are fitted using a parameter optimisation and their root-mean-squared errors relative to the observed data are shown in Table 2.16. For comparison, three other common distributions, which are not commonly used for extreme value analysis are considered as well. (Vrijling & van Gelder, 2006) (Napoles, 2018)

Table 2.16: Fitting distributions and RMSE to hurricane wave height

Distribution	RMSE
Gaussian	34.5623
Gamma	34.4671
Lognormal	34.2173
Frechet	33.8416
Gumbell	33.3458
Inverse Weibull	34.4102

The comparison between the standard and extreme value distributions show that the values are indeed better approximated by extreme value distributions. Gumbell and Fréchet distributions seem to be most accurate overall. The last extreme value distribution considered, the inverse Weibull distribution, approximates the data much less well. This can easily be explained, as this distribution is based on an absolute maximum value possible in the dataset, which cannot be explained by any physical limitations of wave height to develop beyond a certain point (in offshore conditions).

To determine which distribution is most useful to extrapolate from the data, it is relevant to consider the situations in which these distributions are normally used. The Fréchet distribution (or 'fat tail distribution') is often used in situations where a large portion of the values are expected on the high end (resulting in more probability mass on the high-end side of probability density functions). An example of this is a wave spectrum where two main wave directions with strongly different significant wave heights both occur frequently. The Gumbel distribution is a more 'neutral' distribution (in which the probability mass in the high-end tail is somewhat smaller). This distribution is often used for a situation in which a normal condition is occasionally changed for an extreme condition. As this is the case for hurricanes passing the Oasis sector, and the Gumbel distribution has the smallest error compared to the data, extrapolation will be based on the Gumbel distribution. The fits of the various distributions are plotted as probability density function and cumulative density function in Figure 2.24.



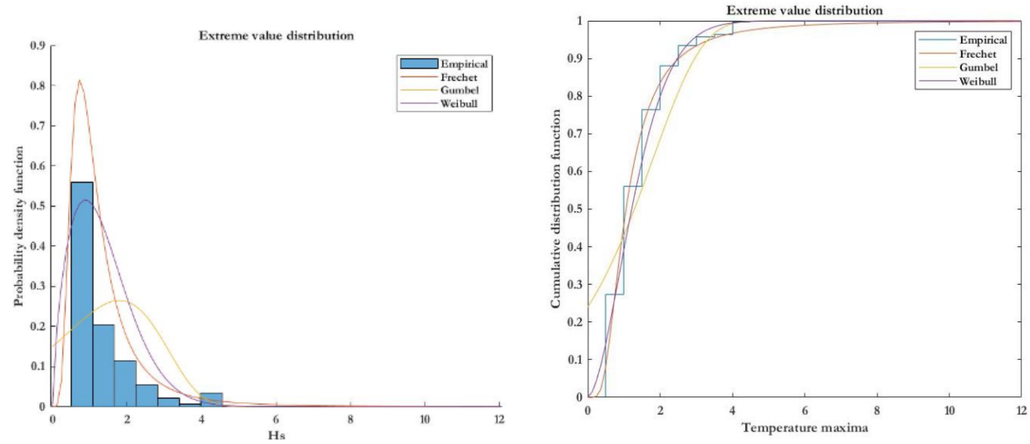


Figure 2.24: Probability and cumulative density functions for various distributions (A-D)

Using the Gumbel distribution, an extrapolation of the expected maximum significant wave height to occur in the future can be made. The approximation is done by bootstrapping our sampled values, which basically means that random values are drawn from the dataset to create a new, larger dataset. This sampling has no preference towards larger of smaller values, but simply serves to acquire more data to reduce inaccuracies in the predictions. (Napoles, 2018)

Figure 2.25 shows the expected maximum significant wave height to occur as a function of the return period of interest. Note that the horizontal axis of the graph has a logarithmic scale. The blue curve shows the fifty-percent confidence interval, meaning that we can say that the maximum significant wave height will be lower than this value with fifty percent security. The five-percent and ninety-five-percent intervals are given as well, to give an indication of the accuracy of the extrapolation.

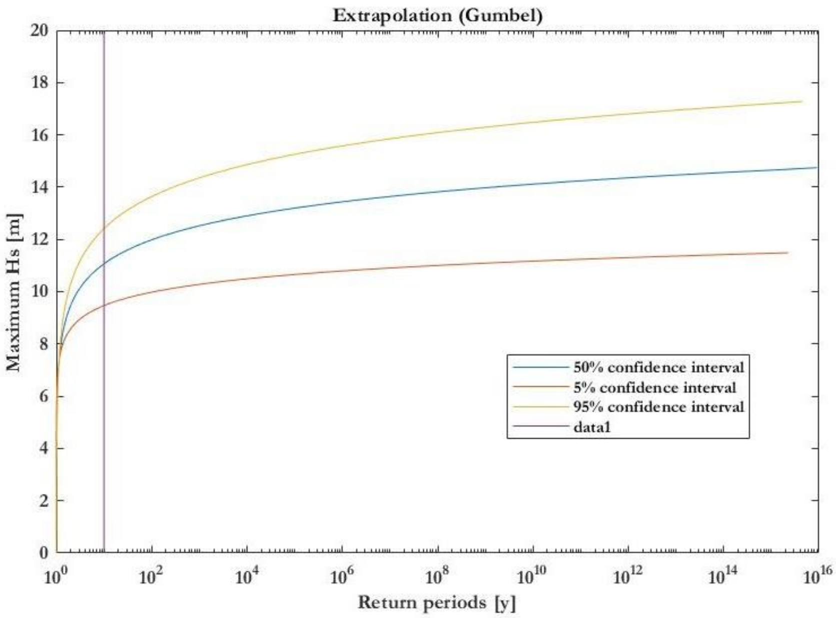


Figure 2.25: Expected maximum significant wave height

A vertical line indicates the design return period of ten years. The following estimates for the significant wave height in extreme conditions can be found.

Table 2.17: Wave height in extreme conditions

Confidence interval [%]	Design value for maximum wave height [m]
5%	9.3
50%	10.9
95%	12.2

Conclusions

To determine which of these design values will be used in the modelling of a hurricane, some final aspects need to be considered. All confidence intervals indicate a rise of the significant wave height for larger periods of time. Please note that this in no way predicts the wave height to grow over time. The rise of the wave height is simply caused by the fact that an extremely large wave height occurring becomes more likely when measured over a thousand years than when measured over ten years. As the samples have been taken over the past eighteen years, the predictions should not be considered accurate for much more than this order of magnitude projected into the future.

As stated at the beginning of this subsection, the values used in the ARGOSS data sampling have been rounded up to half a metre, giving an average additional safety of 0.25 metres (assuming the values are equally distributed in the 0.5 metre intervals). Therefore, we use the (offshore) wave height of 10.9 metres as estimate of the largest wave expected to hit the Oasis beach in the next ten years.

2.6 Conclusions

Though the analyses described in this section range from political and organisational to exact quantifications of parameters, they all provide direct input to the modelling phase in the following section.

From the stakeholder analyses, it has become clear that the most influential stakeholder is the Ministry of Tourism, on whose authority the construction of the Oasis hotel and development of the Oasis beach will take place. Both the Ministry of Construction and the Ministry of Science, Technology and Environment will play a large role in the actual development of the Oasis beach, as they are the legislative authorities with respect to any construction taking place in the coast. The latter ministry will be supported by the Centre of Environmental Services of Matanzas, which specifically focuses on the Matanzas province and intensively monitors the Varadero coastline.

The network analysis determined the most likely bottlenecks during the evacuation of the Hicacos peninsula. The connection between the Avenida Primera and the Autopista Sur at the edge of Varadero town is the first bottleneck. The connection of the Autopista Sur to the Avenida Tra, where the two-lane road is merged into a single-lane road, is the second likely location where congestion will occur. This will be used as reference in the modelling of the evacuation transport flows.

The coastal analysis gave a general impression of the coastline and surrounding oceanographic situation of the Oasis beach. The tidal range on the beach is relatively small at 0.7 metres. The narrow foreshore, on which hardly any wave energy can dissipate is an important factor in the large erosion of this specific beach in Varadero. The Paso Malo groyne on the eastern boundary of the beach stops sediment inflow in normal conditions, which isolates the sediment balance of the Oasis beach from the overall sediment flow of the Hicacos peninsula. In its current state the beach shows large areas of exposed rock and bedrock, making it unsuitable for exploitation by the Oasis hotel.

The wind and wave conditions were analysed, resulting in a representative maximum wave height for extreme conditions. The characteristic values for significant wave height, peak period and wave direction of incidence have been determined as well, which will be used as design conditions in the modelling phase. Based on the design wave height resulting from the storm analysis, hurricanes which resulted in a similar wave height will be modelled.

3. Modelling

Now that all parameters have been defined for the normal, cold front and storm conditions, both for coastal development and simulation of evacuation transport, models will be used to test the design conditions. For the coastal development, the models will help determine the shoreline changes of the Oasis beach and the physical processes which cause these changes, focussing on the effects of hurricanes on the sediment balance of the coast. This information can then be used to determine what measures could contribute to the development of a stable beach.

For the assessment of the evacuation of the Hicacos peninsula in storm conditions, the same storm conditions are considered, and based on various estimates of the growth of tourism in Varadero, the evacuation process will be simulated, resulting in a conclusion on the storm safety of the tourists.

3.1 Alongshore sediment transport

As previously described, the Hicacos peninsula is exposed to normal conditions, cold fronts and hurricanes, see Table 3.1. Due to the varying wave characteristics, the transport along the coastline differs in magnitude and direction throughout the year. According to Kenia Hernandez, engineer at the Cuban engineering bureau Gamma, the peninsula suffers from a yearly coastline regression of 1.2 metre per year. In this section, the different causes of sediment transport are discussed.

Table 3.1: Wave conditions along the Hicacos peninsula

Parameter	Value
Normal conditions	
Hs	0.513 [m]
Tp	4.32 [s]
Dir	67.9 [°]
Duration per year	350 [days]
Cold front conditions	
Hs	2.1 [m]
Tp	7.67 [s]
Dir	315 [°]
Duration per year	15 [days]
Hurricane conditions	
Hs	$0.513 \leq Hs \leq 9.34$ [m]
Tp	$4.32 \leq Tp \leq 25.0$ [s]
Dir	$0 \leq Dir \leq 360$ [°]

Alongshore sediment transport Peninsula de Hicacos

In 2003, an extensive study has been done about the alongshore sediment transport along the Hicacos Peninsula. Using the model software UNIBEST, a transport of 84,000 m3/year westwards. Their findings are in line with the estimate of the Cuban Institute of Oceanology, which estimated the average net alongshore sediment transport at 50,000 m3/year, also in westward direction. This sediment flow is caused by the normal wave climate, cold front conditions and the occurrence of hurricanes. The contribution of hurricanes varies as the quantity of hurricanes and their magnitude and angles of incidence vary strongly per year. For example, where hurricane

Wilma mostly contributed to the cross-shore sediment flux, hurricane Irma acted opposite and was mainly responsible for a longshore sediment transport (Córdova, 2018)

Alongshore sediment transport Oasis Beach

Several causes can be addressed for the shoreline regressions at the Oasis beach. According to (van Dam, van Dijk, Lausman, Over, & Segboer, 2003), the main contributor of the shoreline erosion at the Oasis beach is the Paso Malo channel, orientated Eastwards of the beach. As can be seen visually, see Figure 3.1: Paso Malo investigation. The entrance of the channel is completely blocking the alongshore current. Consequently, the sediment inflow at the Oasis beach reduces to zero. After the shadow zone of the channel entrance, it is trying to return to equilibrium sediment capacity, causing severe erosion at the Oasis beach shoreline. Figure 3.2, obtained from Erosion of the Peninsula, (van Dam, van Dijk, Lausman, Over, & Segboer, 2003) recognizes this explanation. A large gradient is found in the sediment transport after the Paso Malo at x = 900 , which indicates severe erosion.

Figure 3.1: Paso Malo investigation

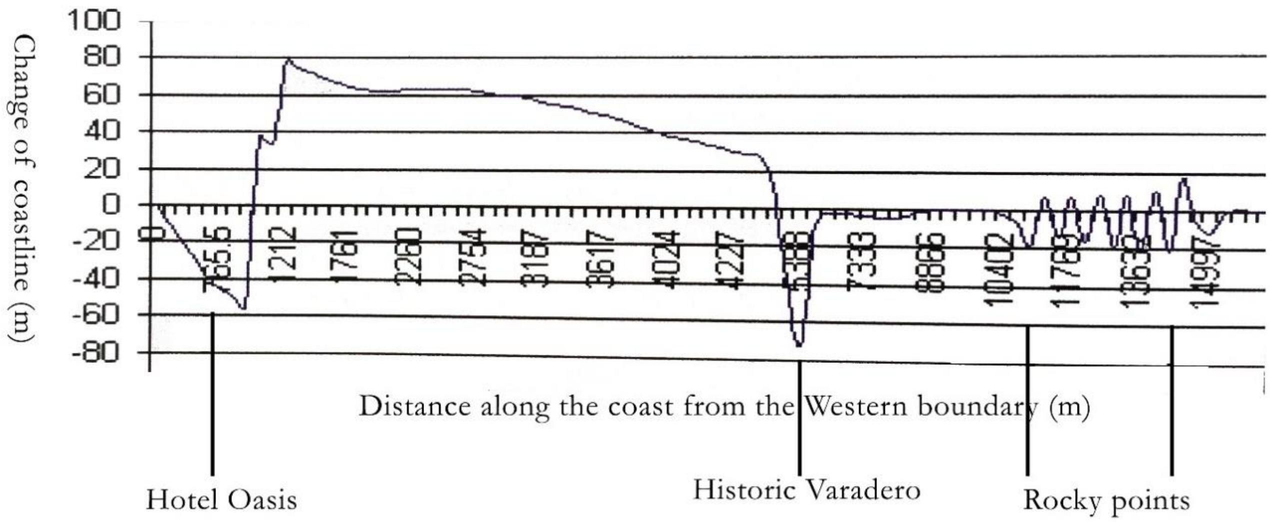


Figure 3.2: Change of coastline

Additionally, local erosion is caused by multiple hard structures near the beach and dunes. The exact influence on the total erosion is not investigated, but according to theory, hard structures on sandy beaches will induce erosion due to sediment blockage, wave reflection and secondary flow patterns.

To further investigate the influence of the Paso Malo channel on the Oasis beach, the coastal analysis software UNIBEST CL+ is used. For a more extensive description of the model used, see Appendix F. Due to the variability in hurricane characteristics, only the influence during normal and cold front conditions is examined. In Appendix F the model setup is discussed. The results of the simulations are shown in Table 3.2. Firstly, simulations are performed with only normal or cold front conditions, to examine the coastal response due to the individual conditions. Additionally, two models are executed with a representative year, including both normal as cold front conditions. To reduce error, the yearly average values are obtained from a 5-year simulation.

Table 3.2: Results of the simulation

Modelled situation	Average regression [m/year]
Normal conditions	
No structures	1.62
PM groyne	0.91
Cold front conditions	
No structures	1.69
PM groyne	-1.56
Representative year	
No structures	1.18
PM groyne	1.14

Conclusion

The influence of the Paso Malo can be extracted from the results in the table above. During normal conditions, the Paso Malo causes a reduction in the average regression per year. During cold fronts, the Oasis beach, with the Paso Malo included, accretes. The sediment transport, running from East to West during cold fronts, is completely blocked, which causes the shoreline to move seawards. When both normal- and cold front conditions are combined, the Paso Malo results in a lower average regression per year, although the difference is not significant.

It must be noted that the UNIBEST CL+ software has limitations regarding the local wave climate in shadow zone of structures (Deltares, 2011). As in this case the influence of the Paso Malo is investigated, it is likely that the actual shoreline retreat differs from the obtained values. However, the model output for a representative year shows similarities with the shoreline retreat given by Kenia Hernandez. Because the outcome is mainly used for obtaining an idea about the influence of the Paso Malo and not for calculations, the results are accepted.

3.2 Storm simulation in ADCIRC/SWAN

Determining a maximum wave height to attack the Oasis beach is only a first step to defining actual storm conditions. To accurately model a storm, a time-varying wave spectrum needs to be defined, for which significant wave heights, peak periods, wave direction and storm surge must be known. Using the extrapolated significant wave height and comparing this to the significant wave heights found for storms which have passed Cuba over the last decades, a suitable storm can be chosen to simulate design conditions for the Oasis beach. Using the NOAA database, two storms have been determined to be suitable for these conditions: Irma (2017) and Wilma (2005) (National Hurrican Center, 2018). Their maximum significant wave heights approach the required value of 10.9 best (9.7 metres and 7.5 metres) and the use of JONSWAP spectra as input result in a slightly higher maximum wave occurring, approaching the required maximum wave height.

Using a pre-existing model developed using a coupling of ADCIRC (Advanced Circulation modelling) and SWAN (Simulating Waves Nearshore), the trajectory and wind speed records of the NOAA for any storm can be used to determine the wave characteristics on any point in a predefined unstructured (triangular) SWAN grid with strongly varying grid sizes, defined in WGS84 coordinates. As Irma and Wilma are the storms that are expected to be closest to our design conditions, specifically the wave height, these storms are analysed in this model. The grid covers the area from the Mexican east coast to a seaward boundary, which curves around Bermuda and Trinidad and Tobago (Figure 3.3).

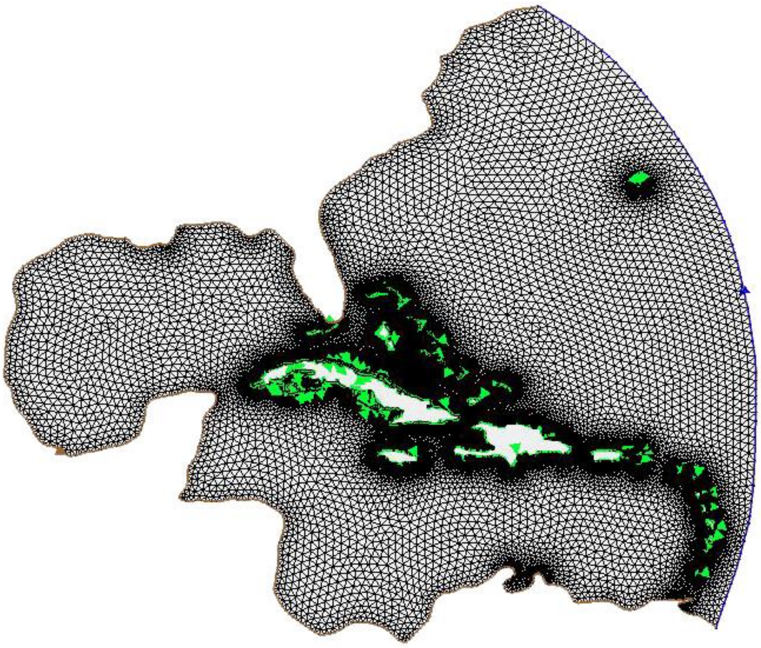


Figure 3.3: Irregular triangular grid used to calculate storm conditions

To acquire information from this grid, three grid points from the SWAN grid are selected to collect data. The coordinates of these grid points are translated to coordinates of the XBeach calculation grid. The ADCIRC/SWAN output is then used as sea boundary condition for the XBeach model.

XBeach (NAD27)	XBeach (WGS84)	ADCIRC/SWAN (WGS84)	Location error [m]
467074.0780, 367579.729	-81.3212001°, 23.138382°	-81.323, 23.1395	222
467515.670, 367654.408	-81.3168901°, 23.1390648°	-81.3236, 23.1407	709
468045.60, 367701.8	-81.3117228°, 23.1395027°	-81.3095, 23.1407	263

XBeach (NAD27)	XBeach (WGS84)	ADCIRC/SWAN (WGS84)	Location error [m]
467074.0780, 367579.729	-81.3212001°, 23.138382°	-81.323, 23.1395	222
467515.670, 367654.408	-81.3168901°, 23.1390648°	-81.3236, 23.1407	709
468045.60, 367701.8	-81.3117228°, 23.1395027°	-81.3095, 23.1407	263

The horizontal difference between the points in the two coordinate systems is shown in . Note that the points are selected to have a similar water depth (of which a maximum error of 0.5 metre is found) and that the horizontal error in location is not of great importance.

Using the location, wind speeds and pressure field of the storm as a dynamic forcing term in this calculation grid, waves are sent in various directions. Three data points on the seaward boundary of the XBeach grid are used to record this output, resulting in hourly values for the offshore significant wave height, peak period, direction and water levels due to storm surge and tide.

Table 3.3: Corner and locations of XBeach

XBeach (NAD27)	XBeach (WGS84)	ADCIRC/SWAN (WGS84)	Location error [m]
467074.0780, 367579.729	-81.3212001°, 23.138382°	-81.323, 23.1395	222
467515.670, 367654.408	-81.3168901°, 23.1390648°	-81.3236, 23.1407	709
468045.60, 367701.8	-81.3117228°, 23.1395027°	-81.3095, 23.1407	263

3.2.1 The ADCIRC/SWAN model

The model used for the simulation of Wilma and Irma runs a simulation of 5 days for each storm, in which the peak of the hurricane is included. Based on the trajectories of the hurricanes, the following start and stop times have been chosen for these hurricanes (National Hurricane Center, 2018).

- Wilma: 21th of October, 2005 0:00 – 26th of October, 2005, 0:00
- Irma: 6th of September, 2017 0:00 – 11th of September, 2017, 0:00

The iterative process of ADCIRC/SWAN

The model is based on the tight coupling of ADCIRC and SWAN, which combines the strength of the of the hydrodynamical and morphodynamical models, leading to an iterative simulation.

SWAN develops the wave conditions based on the and feeds the radiation stress to ADCIRC. Using this input, ADCIRC the morphodynamical effects and changes the bathymetry based on the results. The new bathymetry is then fed to SWAN, which uses this to adjust the spectral parameters. The sweeping method used in SWAN allows it to update wave information over computational vertices of multiple grid points, whereas ADCIRC calculates the bathymetry changes on all points separately for each time step. This means that the ADCIRC part of the model runs a series of calculations with modelling periods of approximately three seconds, after which the SWAN model adapts the spectral conditions in one sweep every 20 minutes. In this way a series of calculations by ADCIRC is alternated by one spectral analysis by SWAN. (Christopher, Miller, Naimaster, & Mahoney, 2012)

3.2.2 Model input

The input of ADCIRC/SWAN consists of various Fort-files, which each contain a specific part of the parameters. The standard bathymetry and grid for a predeveloped model for the irregular grid shown in Figure 3.16 have been used and have not been adapted.

The ADCIRC/SWAN model takes various input files, mostly standardized in the ADCIRC formats (Fort-files), of which only one file provides input to SWAN. (ADCIRC, 2018). The following files are included in this model:

Fort.13

The nodal attributes file. This file includes the stationary points in which local properties can be defined. In the ADCIRC/SWAN model used, all 150,387 nodes are assigned a weight in the overall continuity equation. Most cells have an equal value, but some are weighted a factor four higher, indicating more importance of these cells in the continuity equations.

These cells are weighted more heavily to prevent local errors in sediment continuity, for example in locations where the grid follows a coast line. As the cells here are relatively small, their influence on the total continuity equation is rather small as well, making them more likely to over- or underestimate wave energy fluxes. The coastal zones are often the areas of interest when running the model, as is the case in this project, therefore they are weighed more significantly, to reduce errors in wave parameters closer to the shore.

Fort.15

This file indicates the model parameters and periodic boundary conditions. For this specific case this includes the forcing and output coordinates (indicated in Table 3.4). Other (in this case unused) options as input here are measurement points to provide meteorological output and hydrodynamic output.

Table 3.4: forcing and output coordinates

XBeach (NAD27)	XBeach (WGS84)	ADCIRC/SWAN (WGS84)	Location error [m]
467074.0780, 367579.729	-81.3212001°, 23.138382°	-81.323, 23.1395	222
467515.670, 367654.408	-81.3168901°, 23.1390648°	-81.3236, 23.1407	709
468045.60, 367701.8	-81.3117228°, 23.1395027°	-81.3095, 23.1407	263

XBeach (NAD27)	XBeach (WGS84)	ADCIRC/SWAN (WGS84)	Location error [m]
467074.0780, 367579.729	-81.3212001°, 23.138382°	-81.323, 23.1395	222
467515.670, 367654.408	-81.3168901°, 23.1390648°	-81.3236, 23.1407	709
468045.60, 367701.8	-81.3117228°, 23.1395027°	-81.3095, 23.1407	263

Fort.22

The meteorological input file. This file includes the time series for the storm conditions, indicating location of the storm eye in WGS-84 coordinate and the wind speeds, direction, temperature, rainfall etc in each grid cell. The convenience of this input file is that it takes a standard format, close to the NOAA standard data format. Therefore, all hurricanes recorded in the last decades, can be included in this model relatively easily. In this project case, Wilma (2005) and Irma (2017) have been included.

Fort.26

Only this input file does not provide input to ADCIRC directly. File number 26 provides both the input to SWAN as well as the coupling of ADCIRC and SWAN. The file specifies the same grid for calculation in SWAN as used in ADCIRC and runs in nonstationary mode, which is needed to accurately include the changing forcing of the wave climate by the moving hurricane, which acts as an energy source. (Delft University of Technology, 2018) This file also states how the wave development must be treated. Firstly, the third generation SWAN model is called, which includes the following (note that for processes not included in further explanation, standard settings are used):

Command CONSTANT indicates that a constant breaker index is used, proportional to the dissipation rate. In this case, the breaking parameter alpha is equal to 1.0.

For the inclusion of bottom friction, the MADSEN command is used, indicating that the expression of Madsen et al. (1988) should be activated. This equation is based on an equivalent roughness length scale of the bottom [kn] in metres. This model runs using the default value of 0.05 metres.

The numerical propagation scheme of the model is non-standard. The ADCIRC/SWAN model uses the BSBT command to use a backwards-in-space and backwards-in-time numerical method. (Vuik, van Beek, Vermolen, & van Kan, 2004) This method is the lowest-order method available in SWAN. The use of a low-order method is important in this case, as higher-order methods are both computationally heavy (which is not time-efficient on the large grid size and amount of time steps) and are more likely to become unstable if the grid size does not vary gradually. Due to the complexity of some nearshore areas, a gradual variation is not always possible, making the BSBT method a robust and time-efficient option for this model.

The SWAN input provides some numerical stop conditions to terminate the iterative procedures in the SWAN computations when the wave conditions converge. For this specific model, this is not expected to happen, as the forcing runs throughout the complete simulation time. Finally, the wave characteristics, such as significant wave height, peak period, minimum and maximum frequency and direction of propagation are produced, which are fed into ADCIRC again to determine the bed changes.

3.2.3 Model output

The ADCIRC/SWAN model has been run on the 8-core supercomputer of the Institute of Oceanography. The model delivered hourly spectral data on the three requested locations. The wave parameters were found to be varying between the different measurement locations, but the statistical difference was minimal. Therefore, the assumption has been made to average the ADCIRC/SWAN output points to an alongshore-uniform boundary condition. This loose coupling (coupling by means of running the output of the ADCIRC/SWAN model as input in the XBeach model) has been proven effective for extreme storm conditions and will thus be used to model hurricanes in the XBeach models. (Suh, Kim, & Kim, 2016)

The final input in XBeach consists of a *jonstable*, text file, which defines JONSWAP spectra on hourly intervals throughout the model run, using the significant wave height, peak period and wave direction from ADCIRC/SWAN results characterized the spectra. The water level elevation, consisting of both surge and tide is included in a separate text file, again defined on hourly intervals, but in practice the XBeach model interpolates the tidal levels based on the time steps defined in the model parameters. Examples of these files are included in Appendix G.

The development of significant wave height and storm surge during both storms is shown in Figure 3.4.

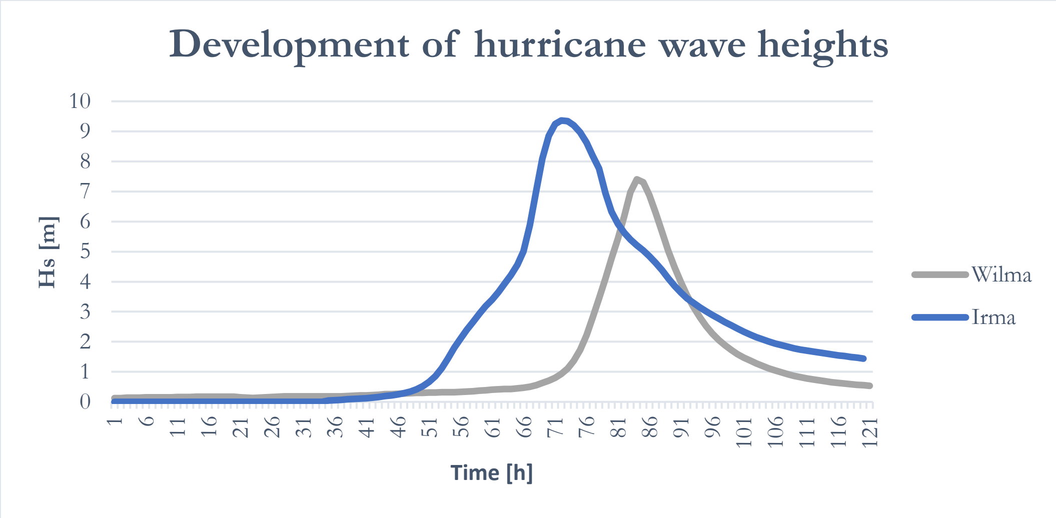


Figure 3.4: The development of significant wave height storm surge

3.3 Modelled conditions and concept designs

This section considers the models and results from the two-dimensional XBeach simulations. As described in section 3.1, the alongshore sediment flow is significant, and a solution is necessary, as the existing Paso Malo groyne blocks all sediment inflow from the east. As the current beach lacks significantly in width, an initial nourishment is included in each model as well. The models differ in the other protective measures. The ADCIRC/SWAN storm output will be used in the input conditions for the hurricane simulation.

3.3.1 Conditions modelled

The conditions in which the beach will fulfil its function, have been described in section 1.6. As normative hurricane conditions, hurricanes Irma and Wilma have been modelled, as they cause a wave climate as close as ever measured to the design conditions defined in section 3.2.

3.3.2 Concept designs

The described basic solution is modelled as a first alternative (zero-reference). This design thus only includes the nourishment; the existing Paso Malo groyne and the new groyne at the western end of the Oasis beach.

Zero-alternative: Nourishment

The necessity of nourishment along Peninsula de Hicacos (22 km), including Oasis beach, has been thoroughly described on multiple occasions by TU Delft students alone:

- Erosion of the Peninsula de Hicacos, Varadero — September 2003
- Erosion of the beach of historic Varadero, Cuba — October 2007
- Varadero Beach — June 2010
- Improving Oasis Beach — April 2014
- Varadero Beach Erosion Project — January 2017

Especially the report Improving Oasis Beach (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014) is a relevant reference project as it concerns the exact same stretch of coast. Herein, a final design for nourishment is set at 150,000 m^3 of Cayo Mono sand. This was taken as a first estimate of nourishment within the project scope of 'Durable Development of Oasis beach' but instantly proved to be excessive within the contemporary project requirements, as stated in section 1.6.

The proposed nourishment shape is shown in Figure 3.5. The beach has a flat surface width of 20 metres, after which it slopes down to the original seabed at a 1:20 slope, leaving total of 40 metres of beach above mean sea level. The nourishment therefore runs to a depth which ranges to approximately 3.0 metres below mean sea level.

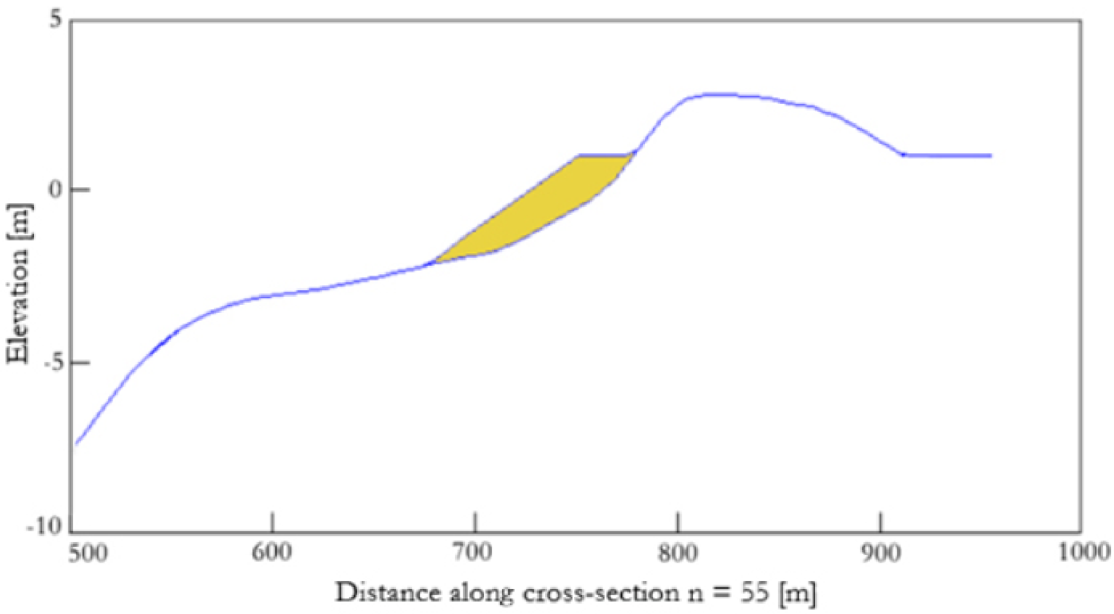


Figure 3.5: Cross-shore profile of nourishment

Nourishment with 40 metres of beach depicted at transect (PX) where a representative dune height of 3.0 metres can be found. The nourishment was implemented in a new bathymetry in XBeach to simulate its functions. The changed bathymetry also results in a first estimate of the nourishment volume by summing up the height difference of the grid and multiplying it by the area of a grid, as follows:

$$V_n = \sum_{i,j}^{N} \Delta h_{I,J} * A$$

In this equation the $\Delta h_{I,J}$ represents the height difference in the grid cell, and A represents the area of the cell, which given the curvilinear grid varies slightly, but for convenience is assumed constant at 50 m^2, as the grid size was defined as 5.0 by 10 metres. The estimated initial nourishment then amounts to approximately 66,000 m^3.

Zero-alternative: Western groyne

The necessity of a groyne at the western boundary of the Oasis beach segment was proven by De Boer, Poelhekke, Schlepers, & Vrolijk (2014). Their work on modelling longshore transport processes was verified before being incorporated into 'Durable Development of Oasis beach'. A secondary functionality of the western groyne could be the partial sheltering of the beach in north-western cold front conditions. Combined with the initial nourishment, this groyne will form the zero-alternative, which is shown in Figure 3.6.

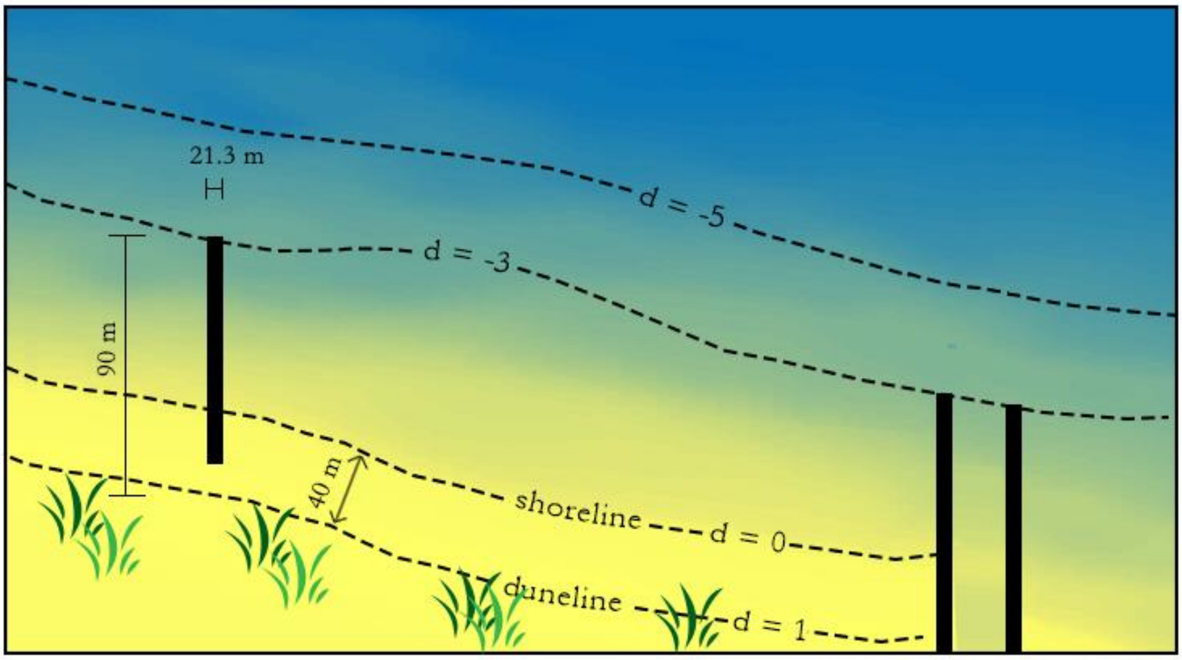


Figure 3.6: Plan view of zero-alternative

A case is made in the report Improving Oasis Beach (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014) for not extending the western groyne to the (then) proposed submerged breakwater at 200 m offshore. A partially submerged groyne extending 70 m offshore is said to encompass every possible mode of longshore transport. In this estimation, a maximum wave height after breaking on the submerged breakwater of 0.8 m is found and converted to a 1.25 m wave considering a maximum fetch of 800 m. Despite analytical backing, the 125 m gap left between the two structures required validation, as hurricane or cold front conditions may lead to water level set-up nearshore, which cause high flow speeds, taking sediment out through this gap.

The final groyne design of De Boer, Poelhekke, Schlepers, & Vrolijk (2014) was taken as initial design for XBeach modelling (w.r.t. geometry, and hydrodynamics). This way, validation of the 2014 groyne design and formulation of the initial design for 'Durable development of Oasis beach' can be done simultaneously (Table 3.5).

Table 3.5: Initial design western groyne

Initial design western groyne		
Geography & Bathymetry	**Design**	**Notes**
Length:	95 m	
Distance offshore:	70 m	
Depth:	-2.5 MSL	Maximum
Geometry of the cross-section		
Structure height:	+2.24 MSL	at -2.5 m MSL
Crest width:	3.0 m	
Slope angle:	1:2	
Hydrodynamics		
Waves W - NW:	3.36 m	Depth-induced
Waves NE - E:	1.76 m	Inner basin
Max. set-up:	1.70 m	Tide and surge

As the final groyne design adopted from the report Improving Oasis Beach (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014) requires filler material from fine (60 mm) quarried material it could be argued that more economical options are available. Submersible caissons or concrete elements may prove to be more economical when readily available ballast materials are used. A sound option here is to use the debris from the existing hard structures once these have been demolished. Impermeability is guaranteed in this design. Either design will suffice in decelerating longshore loss of sediment and should be included in any zero-solution concerning preservation of Oasis beach. Also, the maximum set-up due to tides and surge combined seems quite large. This will be addressed in section 5.3.3.

Alternative 1: Submerged breakwater

The first design alternative is to include a traditional, high-crested submerged breakwater. This breakwater is modelled as an adaption in the bottom profile with a crest width of 10.0 metres and a slope of approximately 1:1.2. This makes the implicit assumption that the breakwater is impermeable, which may overestimate the dissipative qualities. The breakwater crest lies only 0.3 metres below mean water level, which means it lies just underneath the water level at the lowest low water, hence the name high-crested submerged breakwater. The breakwater is connected to the groynes by a shore-normal submerged section, which has the same specifications as the shore-parallel section of the breakwater. A typical cross section of the breakwater is shown in Figure 3.7.

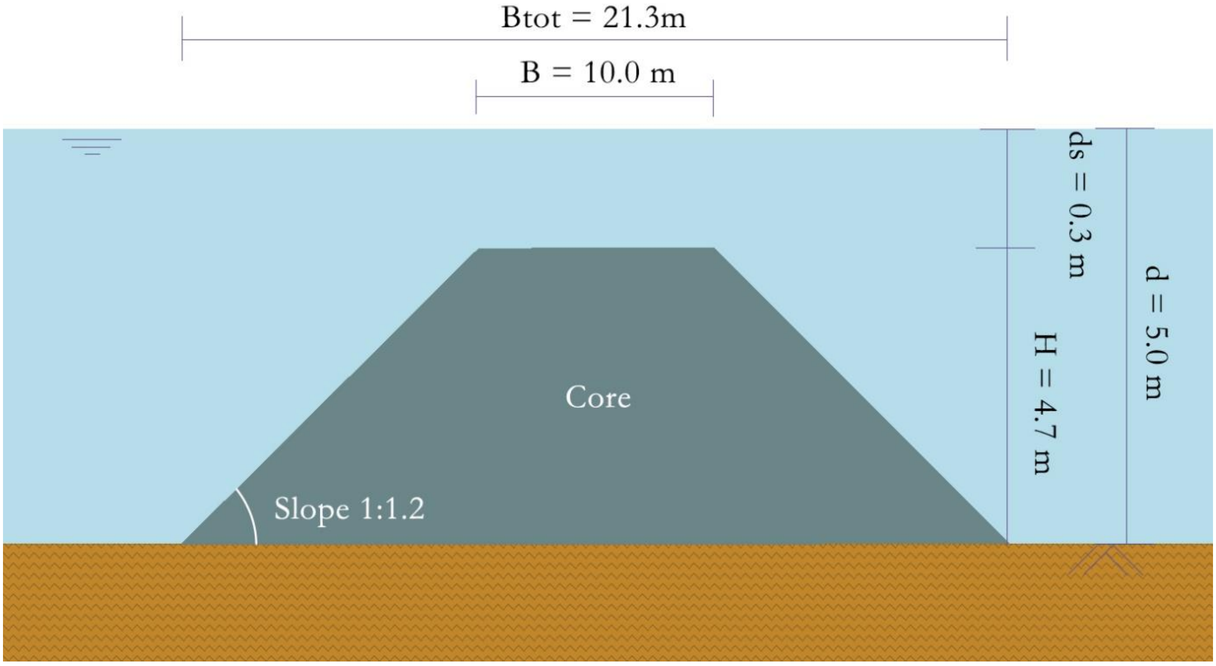


Figure 3.7: Representative cross-section of the breakwater

A submerged breakwater is likely to be the optimal solution for protecting Oasis beach against tropical storms. Emerged breakwaters are not considered a viable option regarding objective 4. Prevention of visual pollution. A choice can be made between a fully submerged structure and one with an intermittently submerged character. The latter implies slight visibility of the structure at low tide and is deemed to still comply with this objective. However, the initial design will attempt full submersion and can be adapted if its wave breaking capacities prove to be insufficient.

The dimensions, cross-shore location, orientation and porosity of the breakwater determine its efficiency. Deliberations about material choice (porosity) will follow in section 5.3.3. The orientation used in the report Improving Oasis Beach (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014) was not adopted. This orientation provides excellent shielding from storms from the northwest (Wilma) but extreme events coming from the northeast (Irma) were not considered. A same orientation would have had severe implications in case the structure was present during the passing of hurricane Irma in 2017. Hence, a shore-parallel orientation is chosen by default.

Definitions of relevant dimensions concerning submerged breakwaters design are shown below.

Location

A few considerations should be made in determining the offshore location of the submerged breakwater. A greater distance from the waterline results in higher costs due to increasing depth while a structure close to the shore is not wanted due to possible current-induced erosion (Dean, Chen, & Browder, 1997). Furthermore, it is preferred to construct the breakwater on a relative flat bathymetry regarding the local stability. Finally, demand B1 must be considered: *"The solution must provide and protect a beach width of 40 metres along the entire Oasis beach section during the complete lifetime."*

Therefore, a minimal swimming zone is defined at 60 metres in length within the boundaries of Oasis beach.

In Figure 3.8 the bathymetry of the Oasis beach is displayed, indicating the depth by colour. The dotted line indicates the 5-metre depth contour. As can be seen, the profile slope is relatively stable before the depth contour compared to further offshore. The average slopes are extracted from the bathymetry data (Gamma Engineering). Depth contour 0 to 5 m show a slope close to 1:20 (nourished) and from depth contour 5 to 10 m the slope falls to around 1:12.5. The depth at 100 metre seawards is found to be 5.0 metres. This location proves to be suitable as it hosts a flat bathymetry and ample space for marine recreation between the waterline and the structure. Another benefit of this location is that sediment transport at this depth is only initiated for extremely high waves, which occur less than once per year.

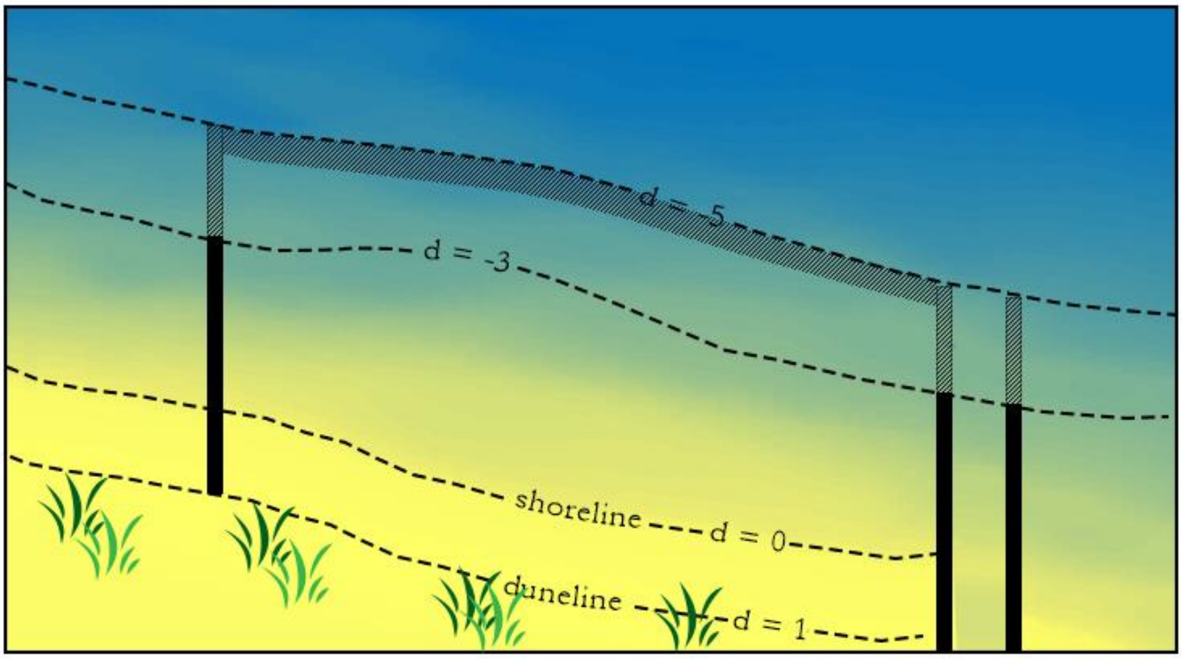


Figure 3.8: Plan view of breakwater alternative

Dimensions

The main objective of a (submerged) breakwater is protecting a coastal area of high wave energy by reducing the incoming wave height. The wave transmission coefficient is a way to describe effectiveness at reaching this objective.

$$K_t = \frac{H_t}{H_i}$$

K_t	Wave transmission coefficient	[-];
H_t	Transmitted wave height	[m];
H_i	Incoming wave height	[m]

Design of (submerged) breakwaters has been described extensively in literature and guidelines. Though the effectiveness of these structures (H_t) is monitored much less. One analysis that provides a scale experiment-based relation between the transmission coefficient and the relative crest width (B/L) is found in (J. Dattatri, 1978). Herein, one submerged breakwater (crest width

B) is monitored using different relative water depths (ds/d) and increasing incoming wave length (L). Figure 3.9 shows the results from this experiment and a conclusion can be drawn that 70% wave height reduction should be possible (ds/d = 0.10). The breakwater will hence be designed for a reduction of 70% of the highest wave found in section 3.2 (H_0 = 10.9 m, T_P = 15 s).

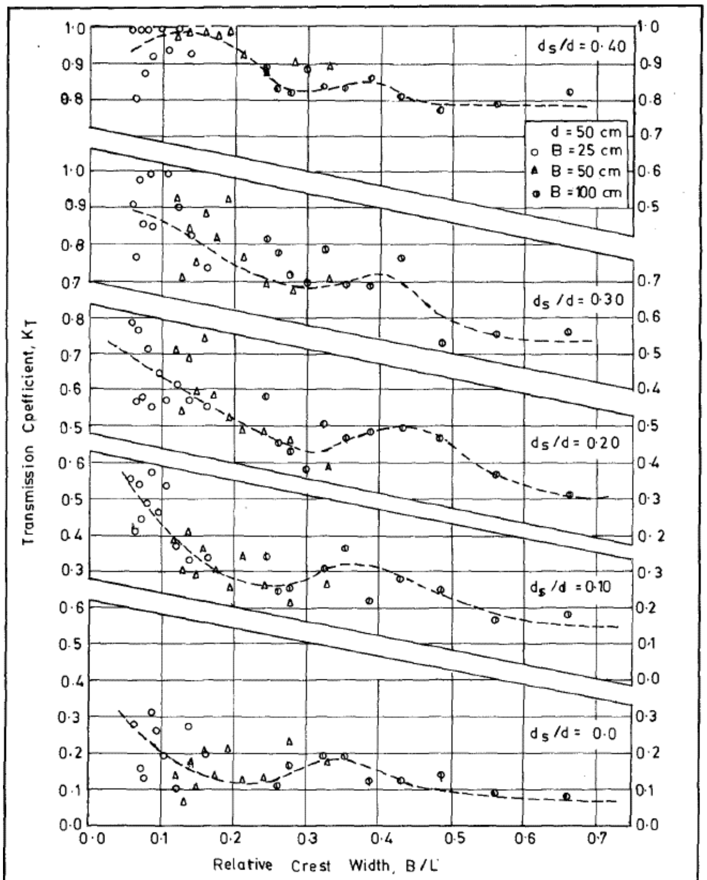


FIG.4 TRANSMISSION COEFFICIENT Vs RELATIVE CREST WIDTH: RECTANGULAR IMPERMEABLE SUBMERGED BREAKWATER.

Figure 3.9: Wave dissipation for varying breaker height

In this graph, the lower two plots are most relevant. For obtaining the desired reduction in wave height, ds/d should be at maximum 0.1, which indicates a depth of crest submergence of 0.5 metre, and preferably less. During low tide in normal conditions, the water level above the breakwater (see section 2.5.1) is 0.25 m. To ensure a submerged crest level, the minimum height ds is set at 0.3 m, which results in a relative water depth of 0.06.

To reduce most wave energy, the relative crest width should be between 0.1 and 0.25 or 0.5 and higher. Considering the costs, only a relative crest width between 0.1 and 0.2 is feasible. To obtain the crest width, the nearshore wave length (L) is required, which can be estimated from figure 5-3 Shoaling, Coastal Dynamics page 162. (Bosboom & Stive, 2015)

This figure describes the relation between the depth, nearshore wave length and offshore wave length. The offshore wave height (L_0) must be determined to acquire the nearshore wave length. The offshore wave celerity and length are found to be 23.3 m/s and 351 m respectively, which results in a nearshore wave length of 105 m. Obtaining the desired wave height reduction of 70%, the B/L should be 0.1, which product a crest width of 10 m.

$$c_0 = \frac{gT}{2\pi}$$

$$L_0 = c_0 * T$$

Preferably, the slope of the breakwater should be as small as possible. However, too small slope could effectuate in geotechnical instability. Therefore, the used slope is set at 1:1.20, as advised by the rock manual. (CIRIA, 2007).

The second alternative is to construct an artificial coral reef, which consists of concrete elements, on which corals grow and develop increasing dissipative qualities. As the solution must fulfil its functions during its entire lifetime, the additional dissipation by coral growth is not included in the model. The elements and additional friction added by the planted corals is included in XBeach as a local bed elevation to a representative height, which is smaller than the height of the concrete elements, as the elements have some open space between them. The effect of the concrete elements and young corals (without accounting for future growth) is modelled as a local increase in bottom friction and short-wave friction. (Ap van Dongeren, 2012)

The third and final alternative is to construct both the breakwater (including the extensions to the groynes) and the coral reef. This combined option is considered to see the effect of combining the measures, and to find whether it is financially viable to add structures, as opposed to performing more regular maintenance nourishments.

Alternative 2: Artificial coral reef

Global seal level rise, worldwide decline of natural systems and the associated erosion problems that many coasts experience call for hydraulic engineering solutions made *with nature* rather than *in nature* (de Vriend, van Koningsveld, Aarninkhof, de Vries, & Baptist, 2015), (Reguero & al., 2018). Not until recently, the scientific community has started to understand the importance of coral reefs in the protection of tropical low-lying coasts (Foley, Stender, Amarjit, Jokiel, & Rodgers, 2014), (Narayan, et al., 2016). As Cuba is known to harbour the most extensive insular coral reef system of the entire Caribbean at 329,000 ha (Goulart, Galán, Nelson, & Soares-Filho, 2017), integrating coral reefs in the design of coastal defence systems seems an opportunity worth investigating.

Definition

The definition of an artificial reef was taken from the General Fisheries Commission for the Mediterranean:

"An artificial reef is a submerged (or partly exposed to tides) structure deliberately placed on the seabed to mimic some functions of a natural reef, such as protecting, regenerating, concentrating and/or enhancing populations of living marine resources. (…) The term excludes artificial islands, cables, pipelines, platforms, mooring, and structures for coastal defence (e.g. breakwaters, dikes, etc.) which are primarily constructed for other purposes…"

- (Fabi, Scarcella, & Spagnolo)

According to this definition, single-purpose-built hydraulic structures cannot be regarded as artificial reefs which is an important facet to the solution.

Layout

Reef cross-sections may be divided into three distinct elements according to visual and energy-dissipating characteristics (Ferrario, et al., 2014). The reef crest marks the offshore locations where a sudden change in bathymetry is caused due to occupation by corals. It is preceded by a sloping fore reef where more sparsely distributed habitats are present. The shoreward hinterland is subsequently called the reef flat in case corals are present on this area (Figure 3.10).

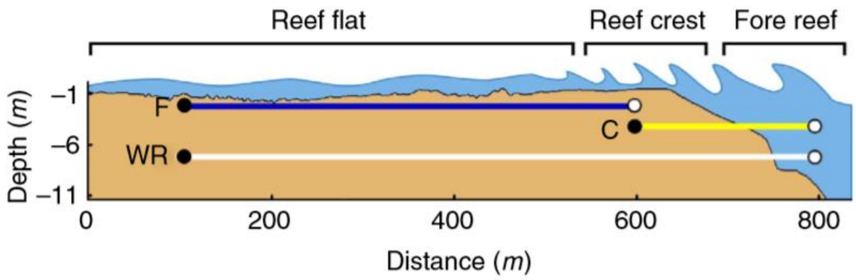


Figure 3.10: Cross-shore profile of coral reef

The depth and cross-shore dimensions are indicative and apply to typical atoll reefs. The target of designing an artificial reef with coast-protective properties is to emulate these visual traits. In doing so, effective wave attenuation is achieved alongside increased aesthetics. An example of such an artificial reef can be seen in Figure 3.11. The reef is approximately 200 metres in length and 10 metres wide.

Figure 3.11: Artificial reef made with Reef Balls ™ in Antigua

Dissipation

Insight in the energy dissipation capacities of reefs has recently begin to develop (Temmerman, et al., 2013), (Gracia, Rangel-Buitrago, Oakley, & Williams, 2017). The previously made distinction between reef flats and reef crests follows from a meta-analysis of 27 independently performed researches on coral reefs (Ferrario, et al., 2014).

Herein, it is found that reef crests show a functionality like that of engineered submerged breakwaters. The abrupt local change in bathymetry caused by the crest can invoke a breaking criterium (e.g. depth-induced, See Sedimentology) for incoming waves. Reef flats on the other hand, have little influence on the overall topography. The dissipation of wave energy on reef flats occurs by wave height reduction due to larger rugosity (coral roughness) (Ferrario, et al., 2014).

A most valuable conclusion drawn from (Ferrario, et al., 2014) is that reefs are not only critical in combatting low-frequency events with high-energy wave attack (e.g. hurricanes) but also in attenuating daily recurring lower energy swell waves and hence reducing structural erosion.

The artificial reef elements that were used in the initial design are the patented Reef Balls ™. Extensive literature and in-practice reports exist on these elements and they have been deployed on many occasions in the Caribbean alone (The Reef Ball Foundation, 2008).

The driving mechanism of these substrate elements are shown in Figure 3.12. Firstly, waves passing overhead a row of Reef Balls ™ are forced to break through depth reduction. Secondly, the return currents coming from the shoreline are guided through holes in the elements. These cause formation of upward vortices upon encountering turbulent flows within the reef system. Finally, these vortices also interfere with wave passage over the reef.

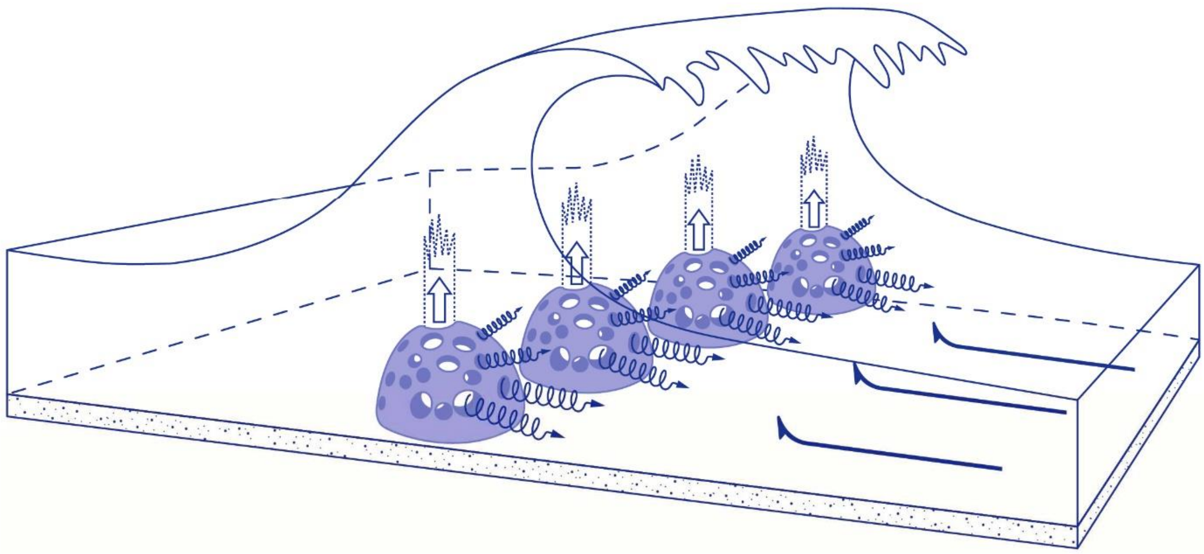


Figure 3.12: Driving mechanism of the substrate elements

A choice will have to be made from the first three classes of Reef Balls ™ (Table 3.6) as these pose the best hydrodynamic performance. The most important assumption that was done for modelling the initial design in XBeach was that the reef flat imposes three changes in parametric conditions to an incoming wave, namely:

1. Bed friction coefficient (c_f) increases due to increased topographical complexity from 0.001 to 0.1 (van Dongeren, et al., 2013).
2. Short wave friction coefficient (f_w) ditto from a value of 0 to 0.06 (van Dongeren, et al., 2013).
3. The height of Reef Balls ™ was reduced to an effective height estimation via the ratio (e) of spherical to cubical volume.

$$e = \frac{4/_3\,\pi r^3}{D^3}$$

With:

e	Effective height factor	[-]
r	Base radius Reef Ball ™	[m]
D	Base diameter Reef Ball ™	[m]

This yields an effective height of 52.1% of the original height for any Reef Ball ™ units. The reef balls are to be placed on the three-meter depth contour. The plan view of this concept is shown in Figure 3.13.

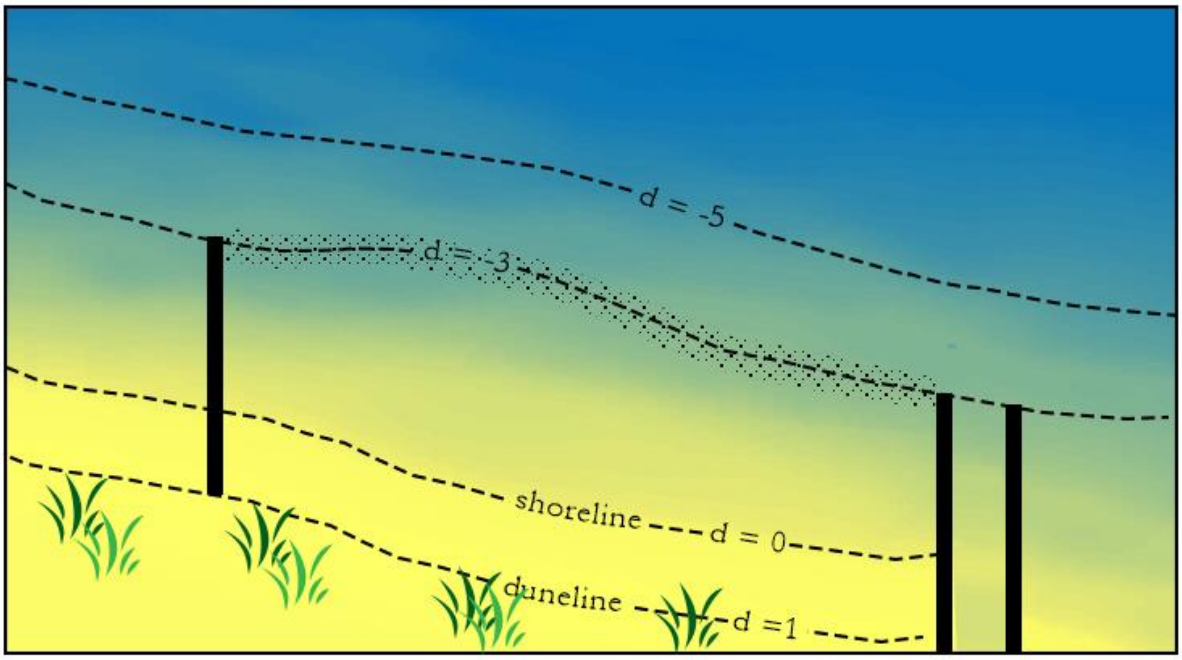


Figure 3.13: Plan view artificial coral reef

3.3.3 Models

The options described above, and the conditions described in section 2.4 and 2.5 result in a range of possible combinations to run a model for. The goal of these models is to find the most viable solution which has the lowest TCO (total cost of ownership) in which maintenance nourishments are included. The option of combining the artificial reef and breakwater is considered as well and is shown in Figure 3.14.

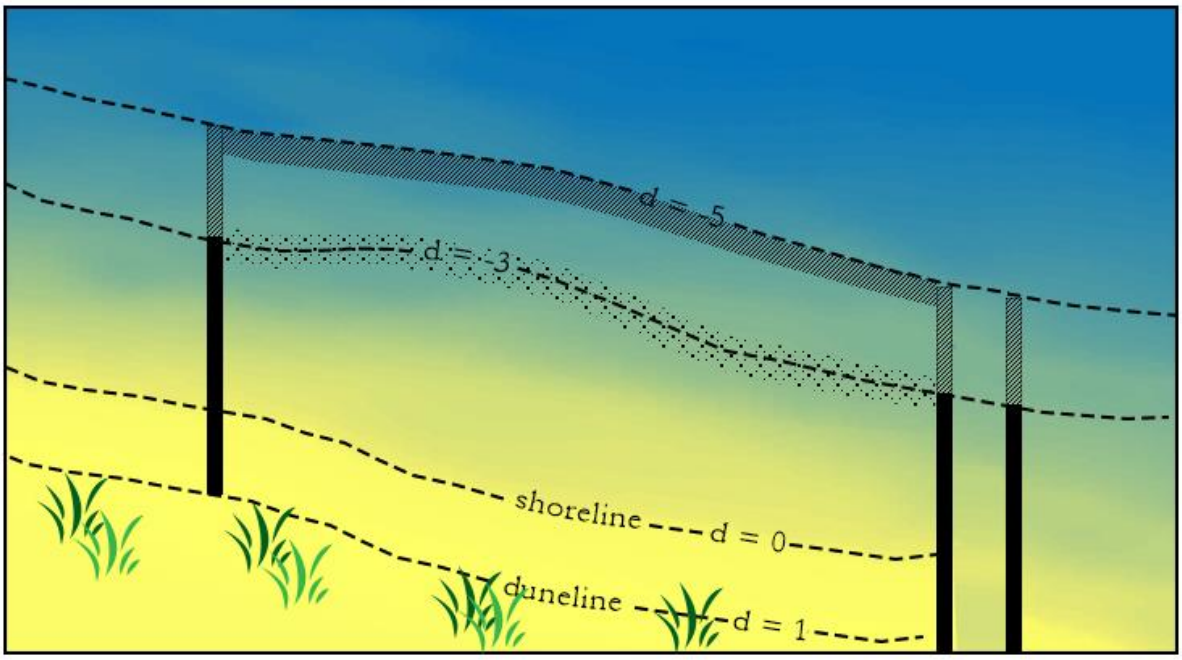


Figure 3.14: Plan view of combined alternatives coral reef and breakwater

Figure 3.14 on the next page provides an overview of all models run. The program used for these models is XBeach. The table is split between included solutions and modelled conditions. The concept solutions will be described directly behind the table. Note that all aspects of the zero-alternative have been marked with '0' and are included in all models, while included additional solution are marked with 'x'. Note that models 9a and 9b test the exact same situation. The only difference between these two models is the morphological acceleration, a numerical parameter for which these models serve as validation test. A description and evaluation of all models is also included in Appendix I.

Table 3.6: Model content list

System							Conditions			
Model No.	**Nourishment**	**West groyne**	**Palo Malo groyne**	**Breakwater**	**Coral reef**	**Extended groynes**	**Normal**	**Cold front**	**Wilma**	**Irma**
Model 1	0	0	0				x			
Model 2	0	0	0					x		
Model 3	0	0	0							x
Model 4	0	0	0		x		x			
Model 5	0	0	0		x			x		
Model 6	0	0	0		x					x
Model 7	0	0	0	x		x		x		
Model 8	0	0	0	x		x				x
Model 9a	0	0	0	x	x	x				x
Model 9b	0	0	0	x	x	x				x
Model 10	0	0	0	x	x	x		x		
Model 11	0	0	0						x	
Model 12	0	0	0		x				x	
Model 13	0	0	0	x		x			x	
Model 14	0	0	0	x	x	x			x	
Model 15	0	0	0	x		x	x			
Model 16	0	0	0	x	x	x	x			

3.4 Cross-shore transport XBeach

The cross-shore sediment transport on Oasis beach has been studied in 2014, based on available wave data and hurricane history at that time. The main issue regarding cross-shore transport on the Oasis beach section is the narrow foreshore with large depth gradients, which impedes sediment transport in landward direction. This shape of the foreshore, combined with the high level of the rocky sublayer makes it difficult to have a sustainable sand layer on the Oasis beach.

The cross-shore sediment is transported by three different systems. The normal conditions are characterized by a small wave energy from the northeast, however, the high energy waves caused by cold fronts and hurricanes cause sizeable erosion, which as described, is only partly compensated during normal conditions, due to the bathymetric profile.

This section connects the gathered information to the models described in section 3.3.3 and Appendix I. The various input files and their contents are listed. Finally, a description of the collected data and the process of creating model input is described for all conditions and beach states.

3.4.1 XBeach

XBeach is a short-term numerical model of nearshore processes for eXtreme Beach behaviour, developed to gain more knowledge in dune safety during storm and hurricane conditions. This process-based model simulates the response of sandy coasts, conceiving dune erosion, overwash and breaching. To do so, the model differentiates four regimes of impact: 1) swash regime, 2) collision regime, 3) overwash regime, 4) inundation regime. In each regime the processes are modelled. The influence of hard structures, coral reefs and vegetation can be incorporated in the model (Dano Roelvink, 2015).

XBeach modulations can be performed in two modes: hydrostatic and non-hydrostatic. Within the hydrostatic mode, two sub-modes are defined: the stationary wave model and the non-stationary wave mode, also called the surfbeat mode. The different modes are briefly described:

- The stationary wave mode neglects all wave-group variations and thus all infragravity motions. Therefore, this mode is only applicable when these variations would be small anyway, which is holding during a moderate wave climate.
- Contrary to the stationary wave mode, the non-stationary mode is especially developed for simulating the impact of storms and hurricanes. During those conditions, the assumption of relative small infragravity motions is no longer valid. The non-stationary mode incorporates this effect by calculating the short waves envelope on the scale of wave groups, see Figure 3.15. This figure is based on Dano Roelvink (2015).
- Whereas the hydrostatic mode only incorporates long wave run up and overwash, the non-hydrostatic mode also includes the short-wave run up and overwash, which is valid for steep slopes, which occur for example on gravel beaches. Furthermore, ship induced waves can be considered due to this characteristic.

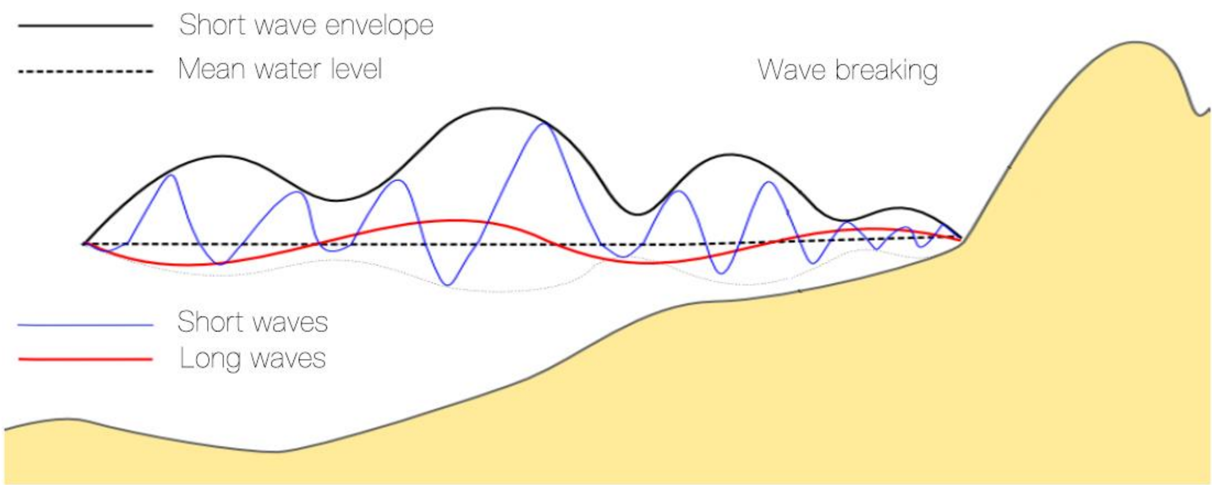


Figure 3.15: Hydrostatic non-stationary mode. The short-wave envelope is calculated taking into account the long wave

3.4.2 Model area of interest

To have the model calculate anything at all, a computational grid is defined (Figure 3.16). The used grid is a curvilinear grid, consisting of cells with an approximate size of 5 metres in cross shore direction and 10 metres in alongshore direction. The grid has 160 cells in cross shore direction and 110 in alongshore direction, making the covered area approximately 800 by 1100 metres. The grid runs from the back of the dunes to a depth of approximately 20 metres and is turned 5 degrees counter clockwise with respect to the North, to ensure the complete dynamic profile during storm conditions is included in the models. Coordinates are given in Cuba-North system, (NAD-27, UTM).

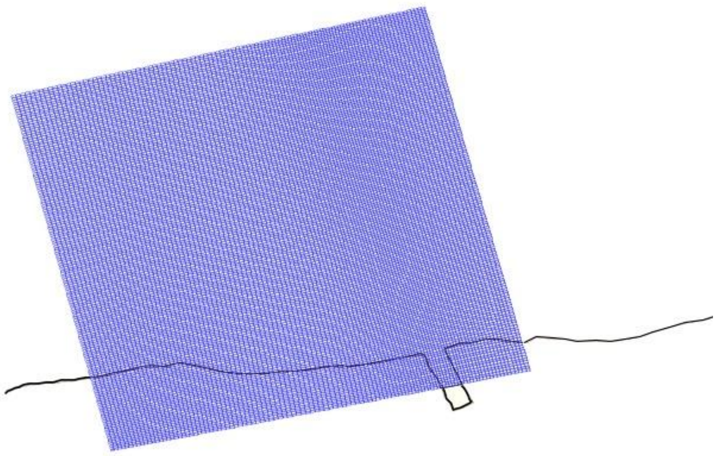


Figure 3.16: Computational grid

All grid cells are used as a control volume during modelling, which means that the outflow of sediment on one cell boundary is used as inflow for the next cell. Using the cell size and these flows, the bed level in the cell is computed for each timestep of the model. These changes are implemented to the predefined depth input, which is described below.

The depth profile of the current Oasis beach has been measured by Gamma engineering. Figure 3.17 shows the measurements both below and above sea level.

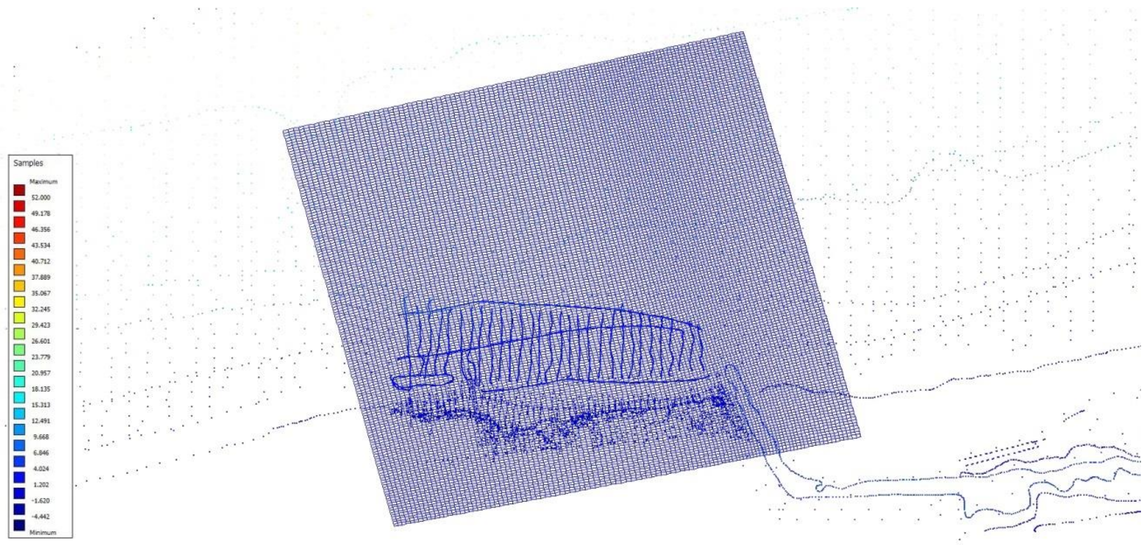


Figure 3.17: Depth profile of the current Oasis Beach

The sampling was significantly less dense in the dune area. As this may lead to unrealistic overwash and return flows in the simulations, data points behind the dunes were added with depth value of 0, meaning that this area lies at sea level. This is a slightly conservative approximation of the actual height, as was observed during a site visit. After the adjustments to the dataset, the bathymetry was interpolated using Delft3D, and the depth was made more realistic by triangular interpolation between the samples and smoothing of the interpolated depth. To form a smooth transition in locations with little samples, additional samples are simulated by the internal diffusion function. This function smoothens the depth further by interpolating between the various data points. The final depth file for the original Oasis beach is shown in Figure 3.18. Note that the z-axis (and thus the depth) are defined as positive downwards. (Gamma Engineering)

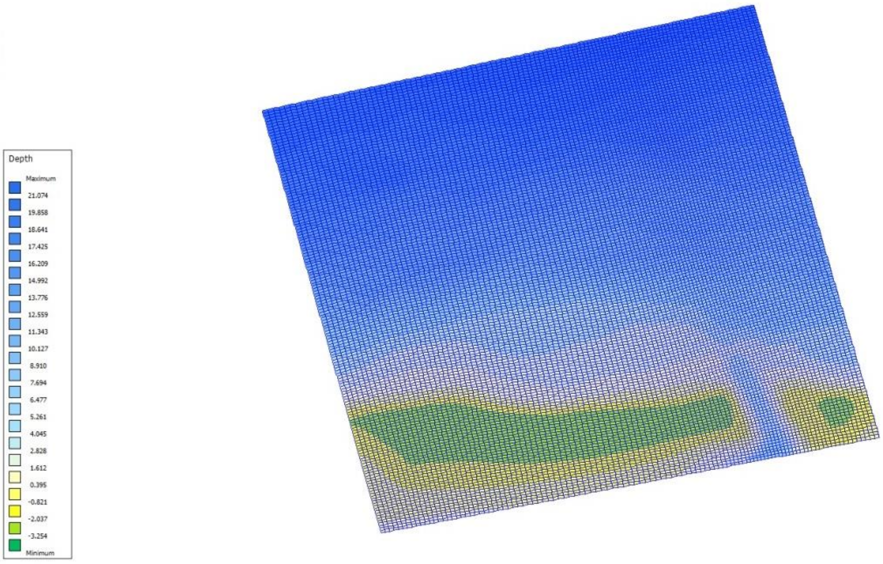


Figure 3.18: Final depth file for original Oasis Beach

An additional depth profile has been defined for a nourished beach. The assumption for this beach is that 20 metres of beach width with a height of 1.0 metre above sea level is present, and 20 metres of 1:20 sloping beach forms the remainder of the required dry beach area. The 1:20 slope is extrapolated seawards until it coincides with the original sea bottom. For clarity, this depth file is shown without grid (Figure 3.19A). Note that the non-erodible height relative to the sand level is defined in a separate depth file, indicating a non-erodible layer, which is shown in Figure 3.19B. This is most relevant in the dunes, where only a part of the profile is sand.

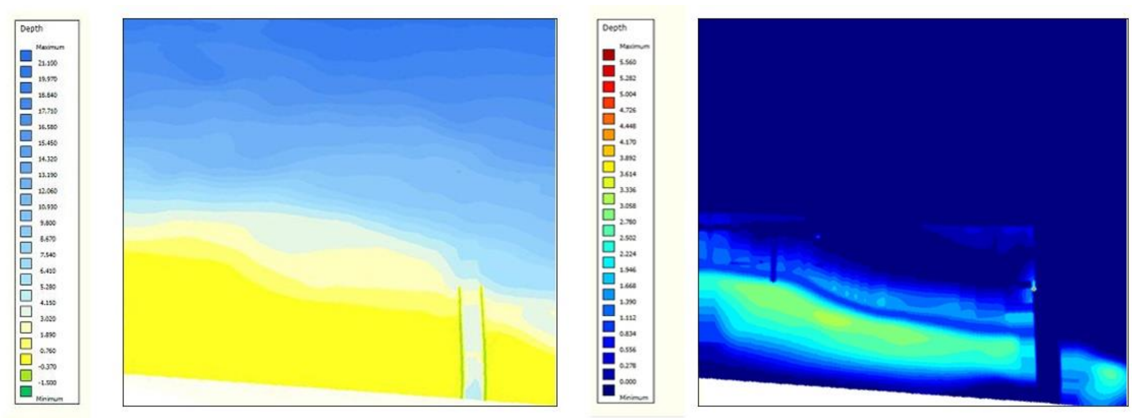


Figure 3.19: Additional depth profile Oasis Beach. (A and B)

The cross-shore profile before and after the nourishment will then look as shown in Figure 3.19.

3.4.3 Model input

The input used in XBeach can be categorized in several types. The following types of input have been used in these models. An example script is given in the Appendix G.

Boundary conditions

Boundary conditions are introduced at the edges of the model to reduce the local inaccuracies. For a representative model, multiple conditions must be specified. XBeach differentiates between wave-, sediment-, cyclic- and shallow water equation boundary conditions. As no sediment inflow occurs during storms (due the Paso Malo channel) and no cyclic behaviour occurs, only the wave- and shallow water equation boundaries are implemented. The boundaries at each of the seaward edges are discussed.

Wave boundary condition

Offshore boundary: waves input is simulated at the offshore edge of the computational grid due to a parameterized spectrum. A JONSWAP table is defined with the wave characteristics: significant wave height, peak period, average wave orientation. Additionally, spectrum characteristics as the Nyquist frequency, the peak enhancement factor and directional spreading coefficient must be provided.

Lateral boundary: on contrary to the offshore edge, no wave conditions are simulated at the lateral boundary. Instead, they are required to reduce local gradients and therefore errors. As the model is used in the surfbeat mode, the XBeach manual prescribes the wave crest boundary instead of the normally default used Neumann boundary.

Shallow water equation boundary condition

Offshore boundary: on contrary to the wave boundary conditions, the offshore and lateral boundaries in the shallow water equations have no physical meaning. As default, XBeach prescribes a weakly reflective boundary condition, also referred to as absorbing-generating condition. This boundary condition ensures that waves and currents can enter the model without disturbances. Lateral boundary: the right and left boundaries of the model domain are representing a continues sea and must be specified to prevent inequalities at the edge. The Neumann boundary condition, default in XBeach, equalises the water level and velocities at both sides of the boundary. Therefore, the Neumann boundary is better known as the 'no-gradient' boundary.

Time varying water level: the tidal signal can be included in the time varying water level boundary. XBeach can use up to four time-varying tidal signals, which can be allocated at one of the following boundaries: offshore-left, offshore-right, backshore-right and backshore-left. Furthermore, a surge level can be included. The model used for simulating the dynamic behaviour of the Oasis beach uses one tidal signal from the seaward boundary which incorporates a time-varying surge level.

Morphology

The Oasis beach includes several hard structures which should be incorporated in the simulation to obtain a realistic output. Luckily, XBeach allows the user to specify a non-erodible layer, in which hard structures and layer can be incorporated. In the model, use is made of this function for describing the bedrock layer, the Paso Malo, the Western groyne and the Coral reef.

To limit the model computation time, it is possible to accelerate the morphological time scale relative to the hydrodynamic time scale. In this case, the waves and currents, which are dependent on the bathymetry, are not updated at the same time step as the bottom change. Accelerating is possible at most conditions, if the hydrodynamics are not too sensitive for bed level changes, which is the case when no alongshore tidal current exists in the model area. The morphological acceleration factor used in the model is 10.

XBeach can incorporate avalanching in the model simulations. A critical dry and whet slope can be defined, which specify the slope below and above water level after which the bed will slide down. Due to this characteristic, XBeach can represent the slumping behaviour of sand during extreme weather conditions.

Modulation time and Output

The models executed during the project had a model time of 3-5 days. Hereby, it is more straight forward to compare different conditions with each other. The output obtained from XBeach is not fixed, but totally variable to the users demands. For the Oasis project, a selection of 20 parameters are extracted from the model, see also Appendix G.

3.4.4 Models run and desired output

The main goal of the coastal modelling analyses is gathering information about the coastal response to the proposed interventions. To obtain a well-founded solution, all aspects of the of the different interventions must be modelled and analysed. Therefore, four interventions will be simulated, intervention input varying from the zero alternative to a submerged breakwater reinforced with an artificial reef and elongated Western groyne and Paso Malo entrance. To represent the weather conditions as realistic as possible, normal-, cold front- and hurricane conditions will be tested, with which the total model runs comes to 16. The desired outcome is a detailed table which links the coastal response, measured in cumulative sediment/erosion, to the intervention method.

3.4.5 Morphological factor validation

Representing reality with models requires a high level of detail, which results in significant computation time. To limit computational time, it is possible to reduce the input parameters, such as wave and tidal conditions, to a minimum. Implementing a morphological factor reduces computational time significantly. This works as follows: Hydrodynamic modules generally require more computational time than morphodynamical modules. A morphological factor extrapolates the hydrodynamic results over a specified number of time steps, instead of computing new hydraulic parameters for each time step. This process works by increasing the depth change by a constant factor, so that after one simulation period in fact *n* periods are computed. (Roelvink, 2006). However, care should be taken with the use of high multiplying factors as they can induce large errors by overestimating variations, inducing unrealistic hydrodynamic changes.

A morphological factor of 10 was used for the XBeach models. This is line with the recommendations of Coastal Dynamics 2, which advise a factor between 0 and 10 for small scale events, during hours to weeks. To validate the usage of the morphological factor of 10, model 9 was simulated twice. Once with the default value of 10 and once with a value of 5, see Figure 3.20Comparing both images, a strongly similar pattern, with limited scale differences can be observed. At most, the left figure has slightly larger sedimentations/erosion rates, which indicates an overestimation using a factor of 10. According to the results in section 3.3.3, the overestimation of the sediment loss in the Oasis sector during hurricane conditions is 7.5%. Hurricane conditions have been used in this validation test, as these are the most dynamic, time-varying conditions used and thus the most sensitive to morphological errors.

Concluding, the use of a morphological factor of 10 in the model simulations will result in a conservative approach, without large errors.

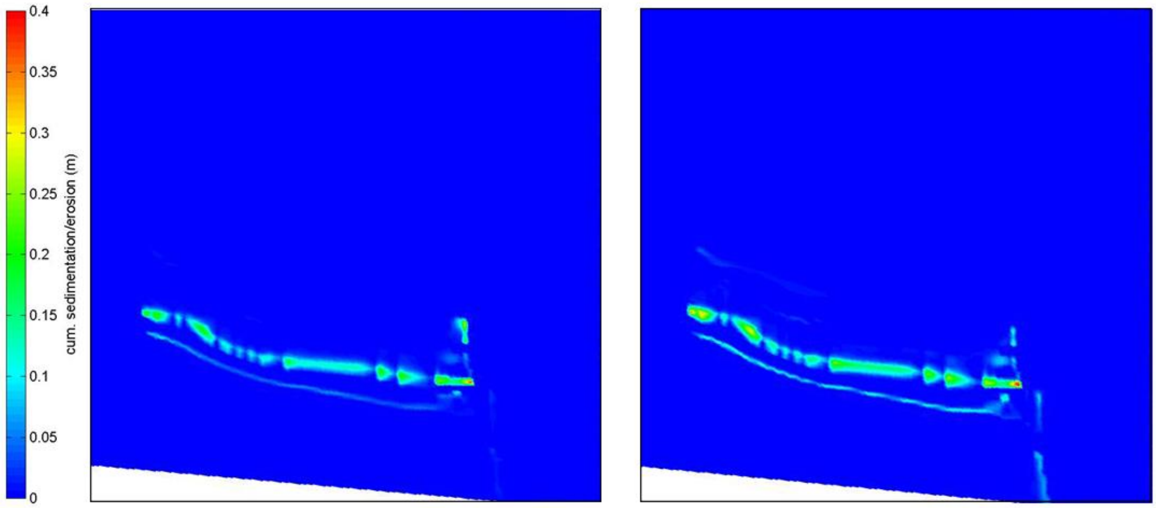


Figure 3.20: Cumulative sedimentation/erosion with morph. factor 5 left and morph factor 10 right

3.5 Evacuation transport simulation

In this section, the evacuation transport simulation model will be explained. This simulation model is used to determine the traffic flow of the current situation. Furthermore, the forecast scenarios as generated in the Network Analysis, are examined. From this analysis, the established critical areas are checked to see if the expected congestion occurs. The simulation model is built using Simio software.

3.5.1 Simio

Simio is a modelling software where 3D animated models of a wide range of dynamic systems can be built and run, to see how they perform. Systems such as factories, supply chains, airport and service systems can be modelled and tested. Simio gives the opportunity to see how the proposed systems will operate over time before they are built or changed. The software uses an object approach to modelling, models are built by combining objects that represent the physical components of the concerned system, such as vehicles, workstations and forklift trucks. Each object is defined by its internal model, consisting of its properties, events, states and logic. The objects internal model responds to events in the system. Simio has a Standard Object Library, this a set of objects that comes standard with Simio, but it is also possible to build a library. To build a model, objects need to be selected from the libraries and graphically placed in the model (Pegden & Sturrock, 2014) (Pegden C. , 2018)

Simio is used for all kinds of systems, but from a modelling point they are all very similar; entities (passengers, trucks, etc) are moving through a system that is constrained by resources (pathways, machines, etc). For these systems the flow of entities through the system and the recourses that constrain that flow are modelled. The systems could beknew proposed systems that have not been built yet or existing systems for which changes are considered. The simulation model is used to verify if the system will perform as is expected (Pegden C. , 2018)

3.5.2 Simulation Evacuation transport model

In step 5 of the evacuation transport model the first four steps are used to predict the traffic flow (section 2.4). Traffic flow models predict how vehicles interact with other traffic and how they drive through the infrastructure network, measuring travel times and dynamically computing congestion. Simulating models are often used to investigate in the traffic flow. In evacuation modelling these models are used to assess the weaknesses and strengths of an evacuation strategy, to adopt a model-predictive framework to design evacuation strategies or to assess the capability of a region during evacuation (Pel, 2017). For this report a simulation model is used to investigate the evacuation capability of the Varadero region and the find the weaknesses of the evacuation strategy. Simio is used to see whether the current infrastructure is sufficient for the future and if not, what adaptions need to be made to make it sufficient again.

3.5.3 Model setup

The peninsula and the connected road to the town Santa Marta and the highway Via Blanca are considered in the simulation model. The peninsula is simplified in the five zones mentioned in section 2.2.1:

1. The latter half of the peninsula from the cross point of the Autopista Sur and Avenida Las Americas.
2. The second half of Varadero town
3. The first half of Varadero town
4. The part of Varadero town south of the Autopista Sur
5. The beginning of the peninsula from the canal Paso Malo till Calle 17 in Varadero Town.

From all five zones, a local road connects the zone to the Autopista Sur, each of them with different distances depending on their position. Capacity of these local roads is not considered, as it is not expected to be normative. The highway 'Autopista Sur' is located from the end to zone 1 to the destination nodes "Santa Marta" and "Via Blanca". The maximum speeds, 100 km/h for the Autopista Sur and to Via Blanca and 60 km/h from Autopista Sur to Santa Marta, and the capacity is set to the number given in section 2.2.5.

The aim is to evacuate the whole population on the peninsula the mainland, either to Santa Marta or to other cities via the Via Blanca. The population meant in this research includes both tourists and locals (inhabitants and employees). Depending on the trajectory of the hurricanes and storms will be determined in what direction the population will be evacuated. Therefore, the evacuation of the population is split in transporting 50% to Santa Marta and 50% to Via Blanca. Vehicles will pick people up from the zones and bring them over the road to their destination. The vehicles will return to their zones to pick up new people via imaginary roads, to simplify and clarify the model. In reality, the vehicles will drive the same route back to and from their zones. The model is shown in Figure 3.21.

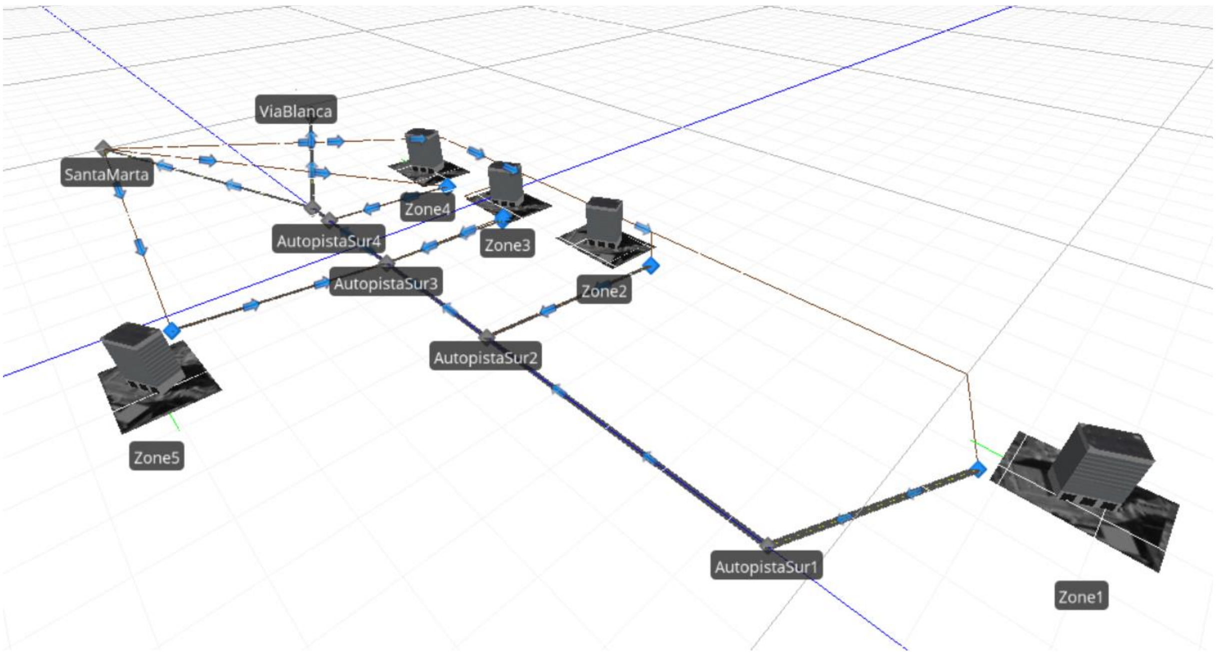


Figure 3.21: The Simio simulation model for the Hicacos peninsula

3.5.4 Model input

As stated in the evacuation analyses (section 2.4.3) the Alert phase of the evacuation plan will start 48 hours before the hurricane is estimated to make landfall. But due to the chances on flood and heavy rainfall on the road as stated in the traffic flow (section 2.2.5) the evacuation time of the model is reduced to a maximum of 24 hours, to be sure that everyone is evacuated in time.

A short overview of the input variables is given in Table 3.7. For more detailed, quantified information and assumptions, see Appendix H.

Table 3.7: Input variables

Variable	Specification
Time	24 hours
Population (entities)	Locals (inhabitants and employees) and Tourists
Vehicles (transporters)	Buses and Cars
Origins (sources)	Zones 1,2,3,4,5
Destinations (sinks)	Santa Marta or Via Blanca

The current distribution of the population is described in the network analysis in section 2.3. To simplify the modes, the population is classified in locals and tourists, locals includes both inhabitants and employees. The distribution in the current situation is given in Table 3.8.

The population is transported by either buses or cars, and as mentioned in section 2.2.3, 60% of the total trips in Cuba is made using buses. Therefore, is this also implemented in the simulation model. As mentioned in section 2.2.3, the buses have a capacity of around 55 persons, and because of the known Cuban neighbouring mentality (section 2.4.3) it is assumed that the average car is occupied with an average of four persons. Furthermore, it is known that only 38 out of 1000 people in Cuba owns a vehicle, so the number of available vehicles in the system is based on the inhabitants. Because the employees do not drive by car to their work but get picked up by buses used for employees only, these people are not considered in the calculation of the number of available cars (González, et al., 2013).

Table 3.8:Distribution of population over the five zones in current situation

Zone	Distribution of populations
1	30% of tourists + 20% locals (20% employees)
2	20% of tourists + 25% locals (13% inhabitants + 12% employees)
3	20% of tourists + 25% locals (12% inhabitants + 13% employees)
4	30 % of tourist + 26% locals (6% inhabitants + 20% employees)
5	4 % locals (4% inhabitants)

3.5.5 Desired output

Different experiments will be simulated, in which various scenarios are implemented in the model and each scenario is replicated five times. In the experiments the population is fixed, but the number and distribution of vehicles differ per scenario. The simulation is done in four different situation; the current situation and the three forecasted situations, as described in section 3.5.4. The model is a non-ending system to see how long it will take to evacuate the peninsula depending on the number of vehicles. Apart from the total evacuation time, the results give insight in what problems occurred in the evacuation process.

Firstly, the current situation is modelled in four scenarios: Two scenarios in which 20% of the total vehicles on the road in the system are buses and the other two with 50% buses, as is mentioned in section 3.5.4. Besides the difference in number of buses, the distribution of the vehicles is also simulated. Two scenarios (one 20% bus and one 50% bus) are run with the number of vehicles equally distributed over the five zones and two scenarios are run where the vehicles are distributed over the zones according to the distribution of the populations. After running the models, the results will show if the number of vehicles is sufficient to evacuate the people, how long this will take and if capacity problems will occur. If evacuation is not completed within 24 hours, new experiments will be simulated to see how many buses and car will be sufficient to safely evacuate within the given time.

Secondly, the same number of buses and cars as in the current situation will be used to simulate all three future situations. In each situation, it will be determined whether the vehicles provide sufficient transport capacity. If not, the experiment will be simulated with a possible solution, like a larger number of cars and buses or an extra lane added to the road. This will continue until the right combination of buses and cars is found and the consequences on the road can be determined.

3.5.6 Sensitivity analysis

To determine the uncertainties of the simulation model, a sensitivity analysis was made. Using small changes in some of the input variables, it was analysed whether the outcomes suit with the expected outcomes. An overview of the analysis is given in Table 3.9.

Table 3.9: Sensitivity analysis

Adaptation	Total time before [h]	Increase or decrease	Total time after [h]	Difference [h]
10% more vehicles	9.11	Decrease	9.08	0.03
10% less vehicles	9.11	Increase	9.12	0.01
10% more population	9.11	Increase	9.14	0.03
10% less population	9.11	Decrease	9.07	0.04

The outcomes of the sensitivity analysis are as expected, but the actual values of the increased or decreased outcomes are less than expected. The simulation model is apparently less sensitive to little changes in the input variables of the model. Nevertheless, the outcomes are as expected, which makes the model predictable and therefore more reliable.

4. Results

This section discusses the results from the XBeach two-dimensional coastal dynamics and Simio evacuation transport models. A comparison between the XBeach models for various solutions and the zero-alternative is shown and the resulting sedimentation and erosion is quantified. The Simio model results show the optimal balance between vehicle types to maximise the use of the road capacity, thus shortening required evacuation time.

4.1 Results XBeach modelling

The models shown in Table 3.6 have been run in XBeach and have been analysed separately, based on visual observation of the output in Quickplot (Delf3D). A full list of observations is presented in appendix I. A summary of the qualitative results will be given here, followed by quantification of the results, for which MATLAB and Openearth tools were used. For reference, the initial bathymetry for various solutions is shown in Figure 4.1 as a comparison for the eroded bathymetries shown for the different structures modelled. The combination of the coral reef and breakwater is not shown, but the location of either structure remains the same.

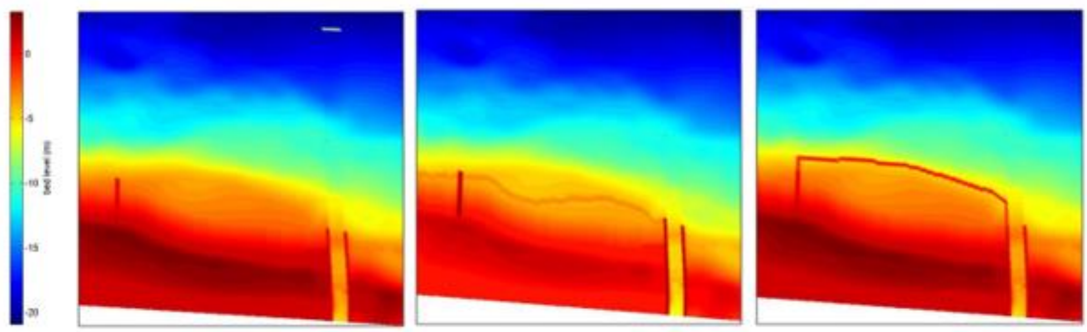


Figure 4.1: Plan view of bathymetries for various solutions

4.1.1 Zero-reference alternative

The zero-reference alternative, including only the beach nourishment, the current Paso Malo groyne and the new groyne on the west side of the Oasis sector, shows significant signs of erosion in all tested conditions. Figure 4.2 indicates the erosion in the various simulations, from left to right: five days of normal conditions, five days of cold front conditions and three days of Hurricane Wilma conditions. Hurricane Irma has also been tested. The visualisations for this model can be found in Appendix I. Note that for the normal conditions, the beach slope still looks gradual, indicating little erosion. For the cold front conditions, a significant volume of sediment has eroded to the foreshore. During hurricane Wilma, the complete beach is eroded away and only the defined hard layers remain, causing a clear transition between the dry shore and the dunes.

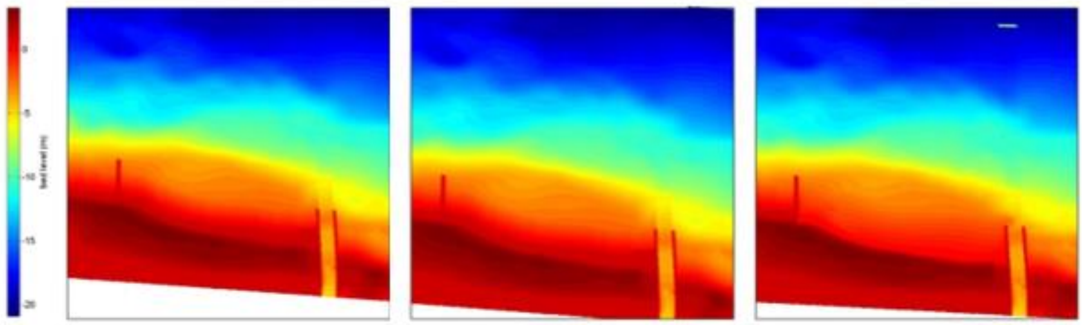


Figure 4.2: Remaining unprotected beach after various conditions

4.1.2 Submerged breakwater

The submerged breakwater alternative, still including the zero-reference alternative, but now including both the offshore submerged breakwater at the five-metre depth contour and the groyne extensions to connect this to the groynes, was expected to protect the beach significantly better, resulting in a much larger retainment of sediment. The visualisations below (again from left to right: five days of normal conditions, five days of cold front conditions and three days of Hurricane Wilma conditions) indicate this to be true, and the beach is no longer completely eroded in the hurricane simulation for models of the Hurricane conditions during Wilma (Figure 4.3) and Irma (Appendix E).

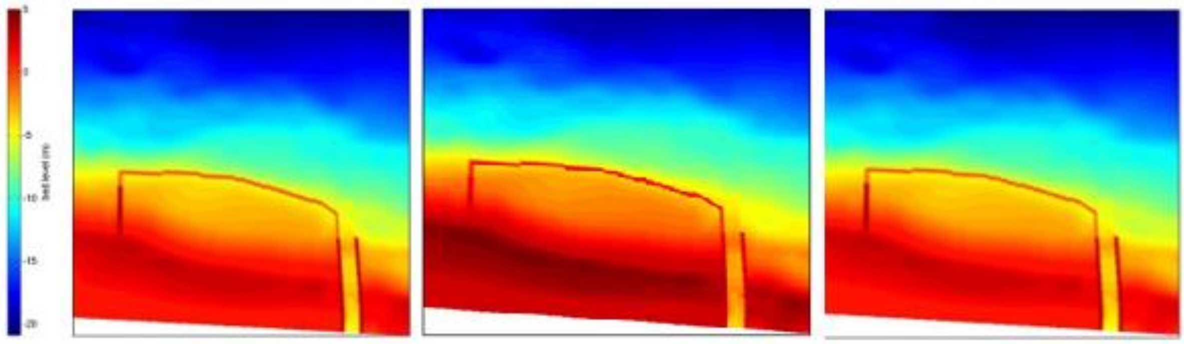


Figure 4.3: Remaining each behind a breakwater after various conditions

4.1.3 Coral reef

The concrete elements on which the coral reef will develop, which are installed at a depth of 3.5 metres, show surprising results. During both normal and cold front conditions (shown in the same order as before), the coral reef seems to stabilise the sediment even better than the breakwater, as can be seen from the left and middle image in Figure 4.4, on which the darker red band near the dune line is still clearly visible, whereas this section of the beach shows to be much more significantly eroded in the case of the submerged breakwater. These effects will be quantified in the following subsection.

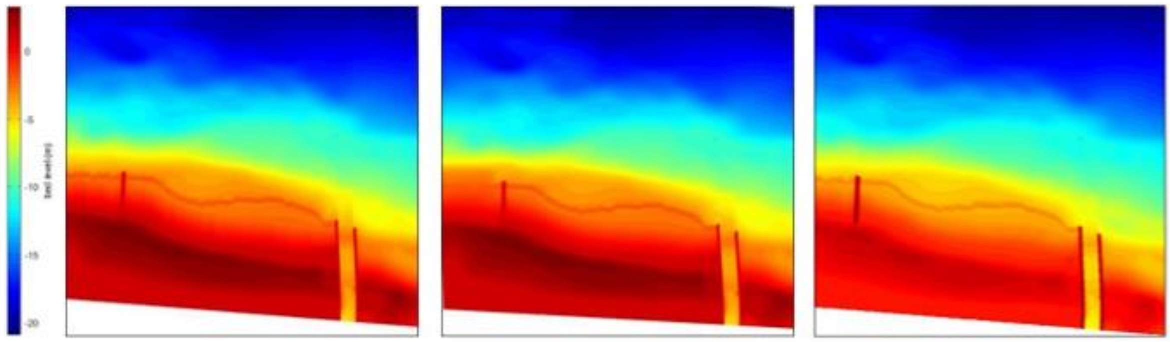


Figure 4.4: Remaining beach behind a coral reef after various conditions

4.1.4 Combined solution

The combined solution, implementing the zero-reference solution, breakwater, groyne extensions and coral reef shows surprisingly little difference with only implementing the coral reef. Figure 4.5 the resulting beach profile after the conditions, again in the order: normal conditions, cold front conditions, hurricane Wilma.

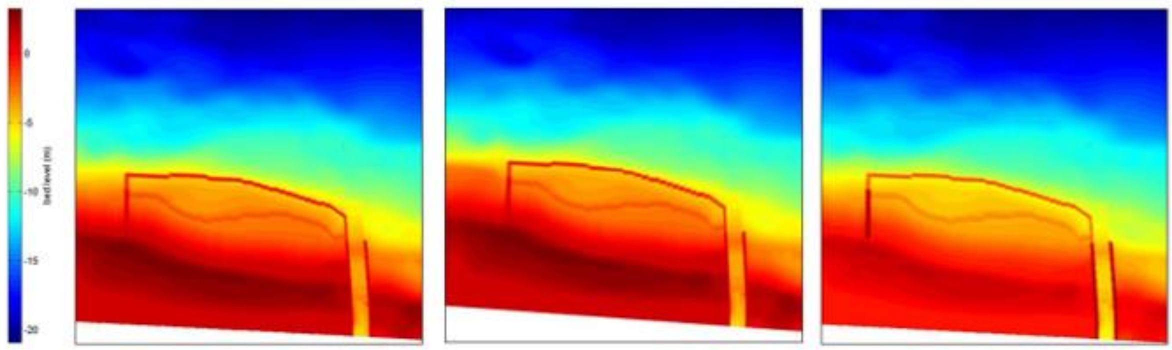


Figure 4.5: Remaining beach with all protective measures after various conditions

Note that the difference between this solution and the coral reef as a separate solution seem to differ only slightly, whereas the erosion of the beach in hurricane conditions is smaller when the solutions are combined. In the following subsections, these effects will be quantified.

4.1.5 Inclusion of dune vegetation

The models of the concept solution showed significant erosion of the dunes in storm conditions, especially for hurricane Wilma, in which a significant surge was combined with almost cross-shore waves. To model erosion in these cases more accurately, three additional models were run for Wilma hurricane conditions, in which the breakwater, coral reef and combined solution are tested again, but two types of vegetation are included. This has been done using the 'vegetation' command in (Deltares, 2015), assigning locations in a vegetation map file, of which an overview is given in Figure 4.6 and assigning the vegetation qualities shown in Table 4.1.

Table 4.1:Model parameters for vegetation

Vegetation type	Matlab name	Value	Unit	Variable description
Trees and bushes	nsec	3	[-]	Amount of vertical sections characterised. The following variables are quantified for the lower (root), middle (stem) and upper (foliage) section.
Trees and bushes	ah	1.0, 1.0, 1.0	[m]	Height of these sections.
Trees and bushes	Cd	2.0, 1.0, 2.0	[-]	Drag coefficient
Trees and bushes	Bv	0.1, 0.3, 0.1	[-]	Vegetation stem diameter
Trees and bushes	N	50, 10, 10	[-]	Number of plants in one grid cell
Grass and moss	ah	0.2	[m]	Height of vegetation (one height section is used here, which XBeach sees as the default setting of nsec, as this is not specified for this type)
Grass and moss	Cd	1.0	[-]	Drag coefficient
Grass and moss	Bv	0.02	[m]	Vegetation stem diameter
Grass and moss	N	1200	[-]	Number of plants in one grid cell

The vegetation modelled is based on a mapping of the present vegetation. (Gamma Engineering) This map, and the vegetation mapping used in XBeach is shown in Figure 4.7. Note that a value of 1 indicated trees and bushes, a value of 2 indicates grassy vegetation and 0 indicates absence of any vegetation.

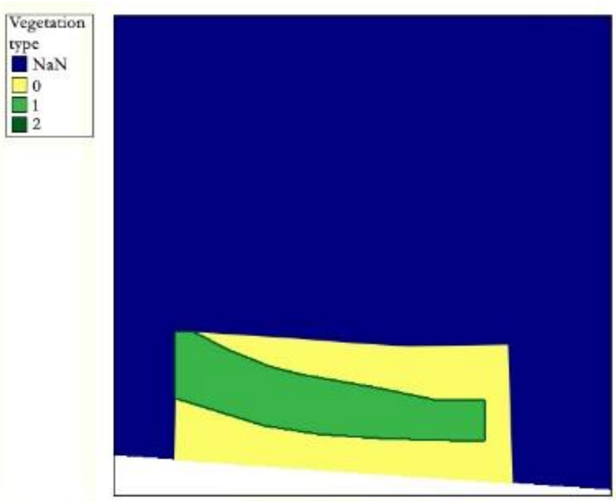


Figure 4.6: XBeach modellation of vegetations

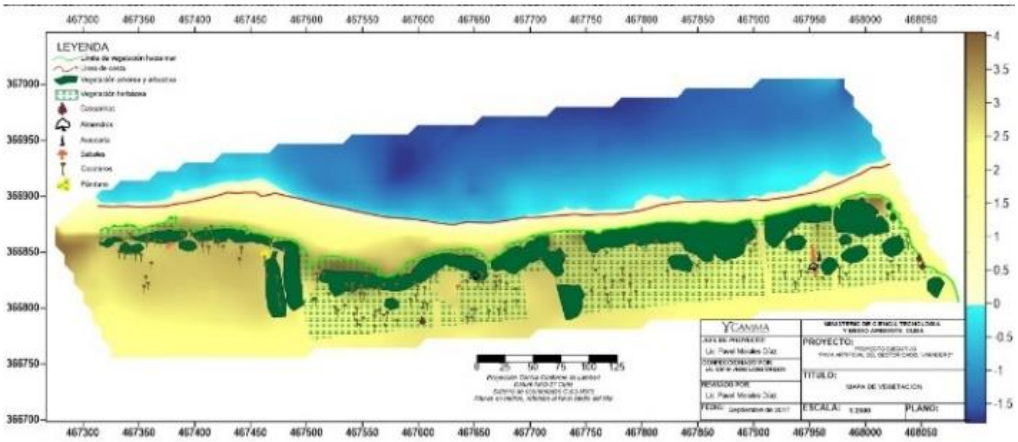


Figure 4.7: Gamma Engineering vegetation map

To determine the effect of the dune vegetation on the beach erosion, three additional models were run. These models correspond to preliminary design models 12, 13 and 14, only differing from these in the fact that the vegetation has been included. An overview of the additional models, which were run for the detailing of the design is shown in Table 4.2. To prevent repetition, the nourishment and groynes are indicated by 'zero-reference solution'.

Table 4.2: Additional models to detail the design

Model no.	Conditions	Corresponding model (without vegetation)	Included measures	Modelled timeframe [days]
Model D1	Wilma	12	- Zero-reference solution - Coral reef - Dune vegetation	3
Model D2	Wilma	13	- Zero-reference solution - Breakwater and groyne extension - Dune vegetation	3
Model D3	Wilma	14	- Zero-reference solution - Breakwater and groyne extension - Coral reef - Dune vegetation	3

The effects of the vegetation on the erosion of the beach are quite clear. The evaluation of all vegetation models can be found in Appendix I. An example for comparison between the models with and without vegetation is shown in Figure 4.8. This figure shows the change in bed level for the Oasis section for model 14 and model D3, which both simulate a coral reef in hurricane Wilma conditions. The only difference is the presence of dune vegetation in model D3.

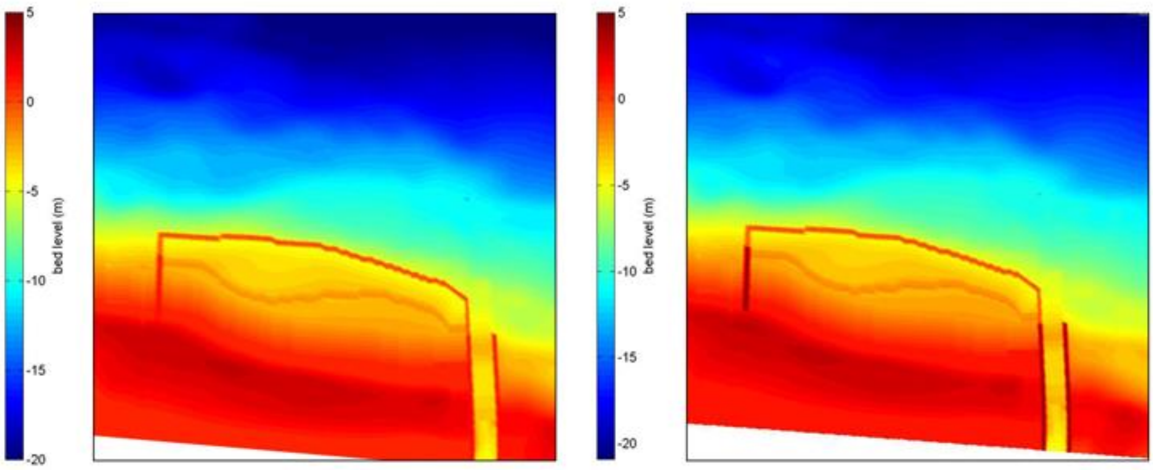


Figure 4.8:Erosion comparison excluding (left) and including (right) dune vegetation

4.1.6 Quantification of erosion

As the evaluation of the models based on the visual output can only be done qualitatively, some further analysis of the XBeach results are needed to determine how the measures affect the required nourishments during the lifetime of 30 years. Using a MATLAB script to read the XBeach netCDF output files, the total erosion of an area can be determined.

To make this calculation, a section was taken from the model to represent the sediment control volume of the Oasis Beach. Figure 4.9 shows the boundaries of this control volume, which runs from the back of the dunes to the six metre-depth contours (thus including a small section seaward of the breakwater and a significant part of the foreshore seaward of the coral reef) and is bounded laterally by both groynes. A 3D bathymetry is shown in Figure 4.10 for further clarification of the used section. This area has been chosen, since the bed level drops several metres over a short distance outside of this boundary, which means sediment is unlikely to be recovered by normal conditions once it is transported out of this area.

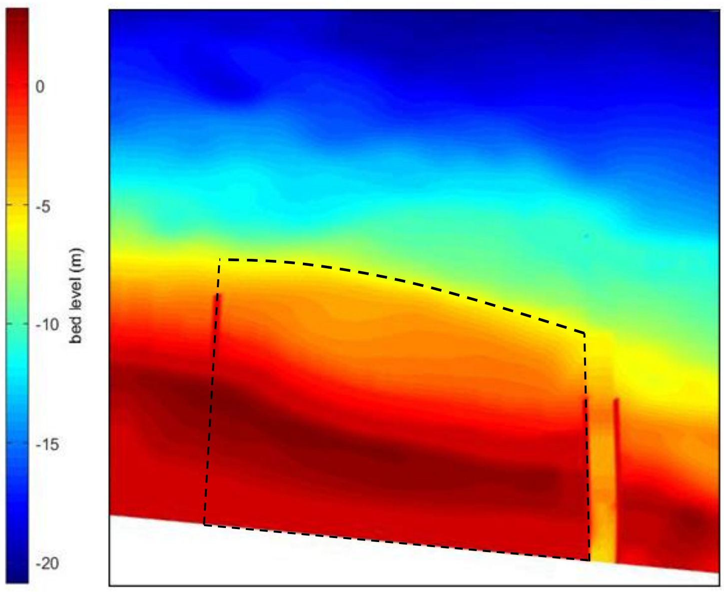


Figure 4.9: Control volume for sediment transport calculation

Using these boundaries, the sediment loss for each simulation was calculated. These losses have been linearly extrapolated to the loss of sediment over one year and the total sediment volume lost over the design lifetime of 30 years, which was specified in requirement L.1. Table 4.3 shows the calculated erosion, model duration and total erosion. Note that for brevity, the initial nourishment and the two groynes are indicated as 'zero-reference solution' in the 'structures' column.

A threshold value for nourishment is set at a loss of 25% of the initial nourishment. In other words: as soon as 15,000 m^3 of sediment is eroded, a nourishment is expected to be carried out. Note that the linear extrapolation over time is likely to cause an overestimation of the sediment lost, as the erosion is expected to reduce with remaining volume of sediment. The sediment volume changes for hurricanes have not been indicated per year but have been indicated as the total over the 30 year lifetime, using the hurricane in the model as the representative 1-in-10-year event.

Table 4.3: Sedimentation, erosion and required nourishments of various solutions

* Please note that volumes are written with a point as a decimal indication and commas as separation of thousands

Model no.	Conditions	Structures	Duration model [days]	Sediment volume change model duration [m3/t]*	Sediment volume change per year [m3/y]*	Sediment volume change in lifetime [m3/30y]*
Model 1	Normal	- Zero-reference solution	5	-98	-6,840	-205,212
Model 2	Cold front	- Zero-reference solution	5	-3,030	-9,696	-290,880
Model 3	Irma	- Zero-reference solution	3	-33,859	N/A	-101,577
Model 4	Normal	- Zero-reference solution - Coral reef	5	-0.08	-5.58	-167.5
Model 5	Cold front	- Zero-reference solution - Coral reef	5	-4.3	-13,76	-412.8
Model 6	Irma	- Zero-reference solution - Coral reef	3	-4,054	N/A	-12,162
Model 7	Cold front	- Zero-reference solution - Breakwater and groyne extension	5	+607	+1,942	+58,272
Model 8	Irma	- Zero-reference solution - Breakwater and groyne extension	3	-9,788	N/A	-29,364
Model 9A	Irma	- Zero-reference solution - Breakwater and groyne extension - Coral reef	3	-657	N/A	-1,971
Model 9B	Irma	- Zero-reference solution - Breakwater and groyne extension - Coral reef	3	-795	N/A	-2,385
Model 10	Cold front	- Zero-reference solution - Breakwater and groyne extension - Coral reef	5	-84	-268.8	-8,064
Model 11	Wilma	- Zero-reference solution	3	-7,994	N/A	-23,982
Model 12	Wilma	- Zero-reference solution - Coral reef	3	-2,917	N/A	-8,751

Model no.	Conditions	Structures	Duration model [days]	Sediment volume change model duration [m3/t]*	Sediment volume change per year [m3/y]*	Sediment volume change in lifetime [m3/30y]*
Model 13	Wilma	- Zero-reference solution - Breakwater and groyne extension	3	-1,630	N/A	-4,890
Model 14	Wilma	- Zero-reference solution - Breakwater and groyne extension - Coral reef	3	-777	N/A	-2,331
Model 15	Normal	- Zero-reference solution - Breakwater and groyne extension	5	-5.2	-362.96	-10,889
Model 16	Normal	- Zero-reference solution - Breakwater and groyne extension - Coral reef	5	0.83	+57.93	+1,738
Model D1	Wilma	- Zero-reference solution - Coral reef - Dune vegetation	3	-2,406	N/A	-7,218
Model D2	Wilma	- Zero-reference solution - Breakwater and groyne extension - Dune vegetation	3	-890	N/A	-2,670
Model D3	Wilma	- Zero-reference solution - Breakwater and groyne extension - Coral reef - Dune vegetation	3	-601	N/A	-1,803

Based on Table 4.3, a range of observations have been made. Firstly, for the zero-reference solution the erosion for hurricane Irma is extremely large, compared to the erosion caused by hurricane Wilma. This difference is smaller in models where more extensive protective measures are implemented. This was likely caused by large alongshore transport due to the large angles between the Irma wave direction and shore normal.

The performance of the various solutions is further described based on their model results in the various conditions. For a final estimate of the required maintenance nourishment, the total erosions using both Wilma and Irma as representative hurricane have been calculated. The required number of nourishments is determined, and a maintenance nourishment is added for every five years of the lifetime, to regularly reshape the beach to the desired profile. As the sediment is transported inside the sediment cell, but most of it does not leave the Oasis sector, it is not required to bring in new sediment for these maintenance nourishments.

Zero-reference solution

The zero-reference solution is still extremely susceptible to erosion, which becomes clear from models one through three and model eleven. Cold fronts are the largest cause of erosion of the beach, however, due to the large timescales in which normal conditions act on the beach, these conditions cause nearly the same volume of erosion. Although a hurricane like Irma causes enormous erosion in the timespan of only a few days, the rarity of these hurricanes makes it a smaller factor in the total erosion.

The total eroded volume over the lifetime of 30 years amounts to almost 600,000 m^3 using Irma as a representative hurricane or just over 500,000 m^3 if Wilma is used as representative storm. The exact eroded volumes are shown in Table 4.3. This means the number of nourishments over the lifetime in case only the groynes and initial nourishments would be placed, ranges between 40 and 46 nourishments (including reshaping of the beach and maintenance nourishments of 15,000m^3) based on hurricane Wilma or Irma respectively.

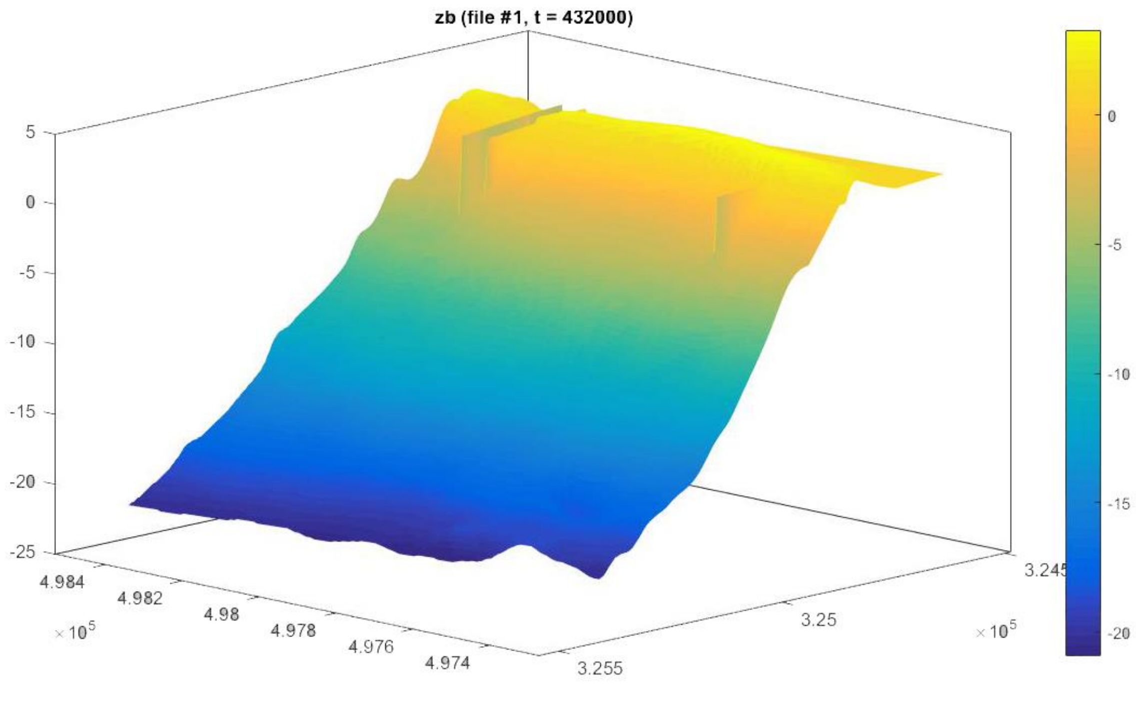


Figure 4.10: Bathymetry of the zero-reference solution

Coral reef

The coral reef reduces the erosion of the Oasis sector significantly. The erosion during normal conditions and cold front conditions is reduced by over 99 percent and the erosion caused by hurricane Irma or Wilma is reduced by 88 or 93 percent respectively. The only weakness showed by the model is that though most of the sediment stays inside the defined control area, large profile changes occur, which may require additional maintenance nourishments.

The total eroded volume over the 30-year lifetime amounts to just under 13,000 m^3, using Irma as representative hurricane. The same calculation based on hurricane Wilma results in a total erosion of a little more than 9,000 m^3. This total erosion is so small that a single, small maintenance nourishment will suffice to maintain the required sediment volume. Including the reshaping nourishments, only seven maintenance nourishments are needed throughout the lifetime.

Submerged breakwater

The proposed breakwater design causes a similar reduction of the erosion as the coral reef in both normal and hurricane conditions. In normal conditions, almost 95 percent of sediment transport is prevented. In hurricane conditions, this is 72 to 95 percent (for Irma and Wilma respectively). During cold front conditions, accretion is expected. Note that due to the location of the offshore boundary of the sediment cell, the accretion is likely to be found mostly outside the breakwater and thus seaward of the area of interest. In Figure 4.11 the wave height development can be seen. There can clearly be noted that the submerge breakwater effectively reduces almost all incoming waves.

The total sediment flow over the lifetime of the breakwater is expected to be positive, meaning the accumulation of sediment near the breakwater in cold front conditions is larger than the erosion during normal and hurricane conditions (using either hurricane as normative). This means only reshaping of the beach slope will be necessary and six of these reshaping nourishments are expected to suffice.

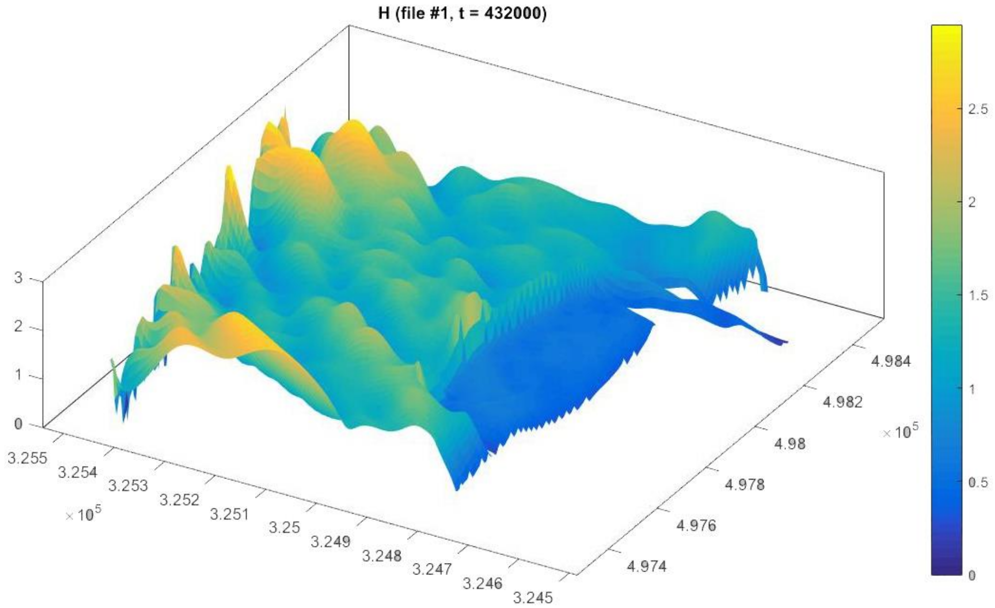


Figure 4.11: Model 7: wave height development when shoaling

Combination of breakwater and coral reef

The interaction between the breakwater and coral reef turn out to be quite relevant for the total sediment transport. In normal conditions, the measures seem to work together quite well, as they cause small accretions. During the sixteen days per year of cold front conditions, erosion is still present, but is reduced by 97 percent. In hurricane conditions, the combination of the breakwater and the coral reef pays off. The erosion during a hurricane with the path and intensity of hurricane Irma, the erosion is reduced by almost 98 percent. The simulation of hurricane Wilma showed a reduction in erosion of just over 98 percent.

The total erosion of the beach is reduced slightly smaller than for the coral reef on its own, amounting to a total volume of approximately 8,000 m^3. For this case, the same maintenance regime holds as for the coral reef. Only one small nourishment with new sediment is needed and including the reshaping of the beach slopes, a total of seven nourishments will be sufficient to maintain the Oasis beach profile. The exact figures of sedimentation and erosion for all simulations are summarized in Table 4.4 and Table 4.5 for the scenarios in which Irma or Wilma respectively is used for estimation. Note that the sediment volume change is negative for erosion.

Table 4.4: Overview of lost sediment and required nourishment for various solutions

Design alternative	Sediment Volume change I [m^3]	Nourishments Irma scenario [-]	Maintenance nourishments [-]	Total nourishments Irma scenario
Zero-solution	-597,669	40	5	**45**
Coral reef	-12,742	1	5	**6**
Breakwater	+18,019	0	5	**5**
Combination	-8,711	1	5	**6**

Table 4.5: Overview of lost sediment and required nourishment for various solutions

	Sediment Volume change W [m³]	Nourishments Wilma scenario [-]	Maintenance nourishments [-]	Total nourishments Wilma scenario
Zero-solution	-508,518	34	5	**39**
Coral reef	-9,331	1	5	**6**
Breakwater	+44,713	0	5	**5**
Combination	-8,129	1	5	**6**

4.1.7 Conclusion

The total number of nourishments required is consistently equal between the Wilma or Irma scenario in all cases where additional structures are placed. For the zero-solution, a significantly higher number of nourishments is needed, resulting in more variation between the scenarios, though for both scenarios an unfavourable nourishment frequency of more than once per year is required. For the Irma-scenario, the nourishment frequency would be 1.5 per year, or once per eight months. For the Wilma-scenario, a nourishment would be needed 1.3 times per year, or approximately once every nine months. In the multicriteria analysis, this will have to be considered for the viability of this option.

4.2 Evacuation transport model

In this section a scenario analysis is done based on the various forecasts of tourism growth. Firstly, the current situation is modelled and the best way to evacuate is determined. Secondly, the same conditions are used to simulate the three scenarios, based on these outcomes suggestions are made to improve the evacuation process. These suggestions are simulated, and the results are used to give an advice on the efficiency of the evacuation process. Detailed information about the simulation and its outcomes can be found in Appendix J.

4.2.1 Current situation

The daily population at this moment consists of 97,581 people and is distributed over the zones according to the percentages given in section 2.2.1. The number of cars is fixed and as mentioned in the network analysis (section 2.1), the distribution of road users in normal circumstances is 20% bus and 80% car. However, this could become 50% bus – 50% car in case of an evacuation. An overview of the input variables is given in Table 4.6. As mentioned in the network analysis, 60% of trips will be made with buses, so 60% of the population will be evacuated by bus.

In total there are four possible scenarios simulated in the current situation:

1. The share of buses is 20% and the number of buses and cars are equally divided over the five zones.
2. The share of buses is 50% and the number of buses and cars are equally divided over the five zones.
3. The share of buses is 20% and the number of buses and cars are divided over the five zones based on the population per zone.
4. The share of buses is 50% and the number of buses and cars are divided over the five zones based on the population per zone.

Table 4.6: The input variables of the current situation

Variable	Quantification
Population	97,581 persons
Number of cars (80%)	798 cars
Number of buses (20%)	200 buses
Number of buses (50%)	798 buses

The resulting evacuation times are given as the number of hours that it will take to evacuate the whole peninsula. As can be seen in Table 4.7, the peninsula will be evacuated within 24 hours in all four possibilities of vehicle distribution. Thus, in the current situation it is possible to evacuate everyone in time, however there is a significant difference between the way of vehicle distribution. If the cars and buses are equally divided over the zones, it will take over one hour extra to evacuate everyone than when the vehicles will be divided according to the distribution of the population. In the current situation, there is little difference in time between the scenario with 50% bus and 50% car and the scenario 20% bus and 80% car. However, this could have influence in the future situation where there will be more people to evacuate. So, both scenarios with vehicles divided based on the distribution of the population will be considered in the scenario analysis.

Besides the total evacuation time, the outcomes also provide the opportunity to see whether congestion occurs, which is especially relevant at the critical infrastructure areas. Fortunately, congestion did not occur on the highway or an of the critical areas determined in section 2.2.5. So, this will not become a problem when immediately evacuation is needed.

Table 4.7:The time needed for evacuation in the current situation

Vehicle distribution	Time [h]
Equally divided 20% buses	9.11
Equally divided 50% buses	9.11
Divided based on population 20% buses	7.79
Divided based on population 50% buses	7.78

4.2.2 Scenario 1. The MinTur forecast

For this forecast the number of daily tourists in 2048 is estimated at 210,000, which gives a total population of 278,208 persons, including the expected Cuban population growth and the growth in employees due to the increase of tourists and accommodations. Because of the population growth will the number of cars also increase from 798 to 806. An overview of the input variables is given in Table 4.8. The distribution of the population over the five zones will in 2048 be changed in comparison with the situation in 2017. Hotels will be built on available ground, which are mostly located in zone 1, causing an increase of tourists to zone 1 and a little decrease in zones 2 and 3. The distribution is represented in Appendix J.

Table 4.8: The input variables of scenario MinTur

Variable	Quantification
Population	278,208 persons
Number of cars (80%)	806 cars
Number of buses (20%)	202 buses
Number of buses (50%)	806 buses

As described in the previous paragraph, the shortest evacuation time is achieved if the vehicles are divided according to the distribution of the population over the five zones. Therefore, these situations are also used by simulation of the three future scenarios, the other situations where the vehicles were equally divided over the zones are not considered any further. The experiment of the scenario MinTur is based on the same conditions as the current situation, so 60% of the population is transported by bus, the outcomes of the experiment are shown in Table 4.9.

Table 4.9: the time needed for evacuation in the scenario MinTur.

Vehicle distribution	Time [h]
Divided based on population 20%	26.96
Divided based on population 50%	26.85

The evacuation time in this scenario will be 26,96 hours without any changes in comparison to the current scenario, meaning that it will not be possible to evacuate everyone in time. To achieve an evacuation time within 24 hours, adjustments need to be made. Table 4.9 also shows that the situation with more buses (increase from 202 to 806) will not have effect on the evacuation time.

A second attempt to decrease the evacuation time was made by changing the distribution of the population over the different vehicles. The first experiment of this scenario was done with the conditions of the current situation, meaning 60% of the population is transported by bus and 40% by car. In the new experiment four new situations are simulated with different distributions of the population, but still with both 20% bus and 50% bus scenarios. The distributions that are used in the simulation are: 60% transported by buses, 70% transported by buses, 50% transported by buses and 40% transported by buses. The outcomes are given in Table 4.10.

Table 4.10 Outcomes of evacuation time in hours by different mode shares

Vehicle distribution	60% by buses	70% By buses	50% by buses	40% by buses
	Time [h]	Time [h]	Time [h]	Time [h]
80% car - 20% bus	26.96	31.14	25.98	31.11
50% car - 50% bus	26.85	31.09	25.97	31.10

The outcomes show that the optimal evacuation time is reached when 50% of the population is transported by buses and the other 50% with cars. Still, the evacuation time is only reduced by one hour to 25.98 hours, which is not enough to evacuate the whole Hicacos peninsula in time. Therefore, a new experiment is done with an increase in number of cars. The current number of cars is considered as a baseline and three more scenarios are simulated having respectively 10%, 20% and 30% more cars than the current situation (Table 4.11). In these experiment, only the scenario with 20% bus and 80% car is taken into account, because the scenario 50% bus and 50% car does not have significant effect on the evacuation time.

Table 4.11: Outcomes of the experiment with an increase in cars

Scenario	Time [h]
80% car - 20% buses	25.98
Increase number of cars with 10%	23.67
Increase number of cars with 20%	22.48
Increase number of cars with 30%	22.47

The increase of number of cars naturally has a positive effect on the evacuation time. Even with a 10% increase of cars the evacuation time becomes less than 24 hours. An increase of 20% still has a large effect on the evacuation time, however 30% does not show that much difference with an increase of 20% cars. Thus, with an increase in number of cars the peninsula can be evacuated in time. The increase in cars does not seem to have effect on the traffic flow during the evacuation, even with a 30% increase in cars will there be no congestion. Hence, the critical areas will still not become a problem during the evacuation of the peninsula.

4.2.3 Scenario 2. The financial forecast

In this scenario the population of the Hicacos peninsula is estimated at 208,208 people of which 140,000 will be tourists. The expected inhabitants and the employees are equal to the MinTur scenario. Therefore, the number of cars and buses are also the same as the previous scenario. The input variables are given in Table 4.12.

Table 4.12: The input variables of scenario Financial

Variable	Quantification
Population	208,208 persons
Number of cars (80%)	806 cars
Number of buses (20%)	202 buses
Number of buses (50%)	806 buses

The first experiment of this scenario is similar to the scenario MinTur, based on the conditions of the current situation. The two scenarios, one with 20% bus and 80% car and the other with 50% bus and 50% car distributed over the zones according to the distribution of the population are used and 60% of the population is transported by buses. The outcomes are given in Table 4.13.

Table 4.13: Time needed for evacuation in the scenario Financial

Vehicle distribtuion	Time [h]
Divided based on population 20%	19.78
Divided based on population 50%	19.91

The results show that without changing the conditions of the current situation, the whole population can be evacuated within time. From the previous section, it is concluded that an increase of cars can decrease the evacuation time to an optimal value. Therefore, these situations are also simulated in a new experiment for this scenario (Table 4.14).

Table 4.14: Outcomes of the experiment with an increase in cars

Scenario	Time [h]
80% car - 20% bus	19.78
Increase number of cars with 10%	17.94
Increase number of cars with 20%	16.67
Increase number of cars with 30%	16.61

The increase of cars also has a positive effect on the evacuation time for this scenario. Similar as in scenario MinTur an increase of cars with only 10% already has a large effect on the evacuation time, 20% causes even more reduction, however between 20% and 30%, the additional reduction of evacuation time is minimal. Furthermore, the critical areas determined in section 2.2.5 do not have a negative effect on the evacuation time, because the road infrastructure is still sufficient for the existing number of vehicles. It is worth noting that contrary to the scenario MinTur, the change in mode share on the road does not have much effect on the evacuation time.

4.2.4 Scenario 3. The linear trend forecast

In the third and last scenario the number of tourists is increased to 75,000 persons per day, which leads to a total of 143,208 people as the population of the Hicacos peninsula. This includes the number of inhabitants and employees that are also used in the previous forecast scenarios. An overview of the input variables is given in Table 4.15.

Table 4.15: The input variables of scenario Linear trend

Variable	Quantification
Population	143,208 persons
Number of cars (80%)	806 cars
Number of buses (20%)	202 buses
Number of buses (50%)	806 buses

Similar to the previous scenarios is the first experiment based on the conditions used in the current situation. The number of cars and buses are distributed based on the number of people in the zones and again, 60% of the population transported with buses. The evacuation time needed to evacuate based on these conditions is given in Table 4.16.

Table 4.16: Time needed for evacuation in the scenario Linear trend

Vehicle distribution	Time [h]
Divided based on population 20%	13.33
Divided based on population 50%	13.28

If this forecast will become true the time to evacuate the Hicacos peninsula will be around 13.5 hours, this is within the 24 hours and tourists will not be in danger. To see if the adjustments made in the previous scenarios will also have a positive effect on the evacuation time in this scenario, a new experiment is simulated to model these adjustments. The results are shown in Table 4.17.

Table 4.17: Outcomes of the experiment with an increase in cars

Scenario	Time [h]
80% car – 20% bus	13.87
Increase number of cars with 10%	12.69
Increase number of cars with 20%	11.69
Increase number of cars with 30%	11.16

Note that the change in mode share from 60% of the population transported by buses to 50% transported by buses does not have a positive effect on the time for evacuation, it even increases by 0.5 hours. Furthermore, the increase in number of cars again has a positive effect on the time that is needed to evacuate. The time decreases everytime the number of cars is increased.

4.2.5 Conclusion

While simulating the current situation, it turned out that there was a significant difference between the needed evacuate time in case the vehicles are equally distributed to the zones and in case the vehicles get distributed according to the distribution of the population in the zones. Furthermore, with the simulation of the current situation the effect of the share of buses on the road has also been determined. In normal situations is assumed that 20% of the road users are buses, but it was assumed that this could be increased to 50% whenever there is an emergency. It could be concluded that this increase of buses did not have the expected effect and did not cause an significant decrease in evacuation time.

The three scenarios with different forecasts of the increase in tourism are first simulated under the conditions of the current situation. It appeared that in scenarios Financial and Linear trend these conditions will be sufficient to get the peninsula evacuation within 24 hours, but for the scenario MinTur it will not. Therefore, several other experiments are simulated, and it turned out that a shift in distribution of the people amongst the different vehicles could help. When only 50% of the population instead of 60% will be transported with buses, the evacuation time will be decreased. However, this only seems to be helpful with a large population such as in the MinTur scenario. In scenario Financial does this change not have a significant effect and in scenario Linear caused this change even an increase in evacuation time. Lastly, an increase in number of cars is simulated. For each scenario an experiment has been simulated with different number of cars and in all scenarios the evacuation time was decreased significantly.

Thus, in case of evacuation it is important to pay attention how the buses and cars are distributed on the peninsula. The evacuation will be the most efficient if the vehicles are distributed according to the population on the island. Furthermore, if the scenario MinTur will become true and there will be 210.000 tourists on the peninsula, an increase in the number of cars of at least 20% is needed to facilitate safe evacuation. The distribution of the population along buses and cars needs to be done carefully, because it will the most efficient if only 50% of the population will be transported by buses.

5. Solutions coastal development

The modelling of coastal designs can be interpreted to assess what solutions are viable to develop and stabilize the Oasis beach. This section will go into more detail on the definitive design of these measures and will specify a total cost and work method for the final solutions.

5.1 Multi Criteria Analysis

Earlier, the necessity of a western groyne and maintenance nourishment at Oasis beach were established in section 4.1.1. Moreover, two coastal interventions to counter losses in cross-shore direction were proposed. The submerged breakwater dissipates wave energy rather efficiently but is expected to require a large initial investment. For this reason, an artificial reef based on concrete elements was proposed. In this section the suitability of the proposed coastal interventions will be assessed using a Multi Criteria Analysis (MCA).

5.1.1 Criteria

This score system uses a predetermined set of criteria that have different weighted values based on their importance to the scope of the project. The entire MCA can be found in Appendix K. For the 'Durable Development of Oasis Beach' we define the following criteria, based on the criteria used in earlier research done on the Oasis Beach. (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014):

Protection against erosion

Alternatives have been tested by XBeach simulations for normal, cold front and hurricane conditions (see section 3.4). As the zero-reference solution includes two groynes, which provide a lateral boundary and stop alongshore sediment transport, the possible solutions focus mostly on cross-shore transport prevention. This criterion is quantified by referencing the sediment losses calculated in section 3.1.

Maintenance

The proper upkeep of built interventions is important to its coastal defence capacities. Values were awarded for associated nourishment frequency required to keep the beach profile constant, robustness of the structures in case of large loads, nuisance of performing maintenance on the structures and technical complexity of the upkeep.

Spatial quality

Spatial quality focuses on the attractiveness of the area, which is relevant, as it will be a recreational area. This criterion aims to quantify the degree of horizon pollution, determined by the height of structures with respect to mean sea level and the overall attractiveness of the beach.

Recreational quality

The project scope, in the end, comes down to increasing the recreational value of Oasis beach. Mitigating erosion is the most important step in achieving this goal but the associated ergonomics (ease of swimming, additional recreational value etc.) were considered as well.

Construction

This criterion deals with the constructability of the designs in Cuba. The goal of this criterion is to quantify whether a solution is constructible for Cuban contractors or is excessively complex. The criterion also aims to quantify whether the required materials are readily available in Cuba.

Environment

No contemporary engineering project should be executed without considering possible environmental effects. Interventions will be valued according to the impact of the design on the alongshore sediment transport, to see if the structures negatively affect sediment inflow to other beach sections. Furthermore, environmental impact of fabrication and transport of materials is considered. Finally, the impact of the structure on biodiversity in the Oasis beach sector is considered.

Risk

Designs range from strictly traditional to more cutting-edge designs. Based on the degree of complexity of a design and experience with the construction method, the risks to the success of a solution can vary greatly. The degree of uncertainty in the quality of the solution is quantified as complexity risk.

5.1.2 Weight factors

The previously described criteria will be assigned weight factors according to their importance in the scope of 'Durable Development of Oasis beach (Table 5.1). This factor will act as a multiplier on their score after which the scores for each proposed alternative will be summed. The highest score from this final step will theoretically be the preferred alternative.

Naturally, the outcome of the MCA will be discarded, should it conflict with any of the requirements or objectives (section 1.5 and 1.6).

Table 5.1: MCA Criteria

Criteria for coastal intervention alternatives MCA	
Criterion	**Description**
1 Protection against erosion	
1.1 Normal conditions	Protection against erosion in normal conditions
1.2 Cold fronts	Protection against erosion due to cold fronts - frequent event.
1.3 Hurricanes	Protection against erosion due to hurricanes - extreme event.
2 Maintenance	
2.1 Nourishment	Frequency of required periodic nourishments
2.2 Structural	Robustness of the structures, number of predictable weak spots
2.3 Nuisance	Impact on recreation during maintenance
2.4 Complexity	Required submerged works and need for heavy equipment
3 Spatial quality	
3.1 Visual	Ocean view and visibility of structures
3.2 Beach	Dimension, capacity and attractiveness of the beach
4 Recreational quality	
4.1 Swimming	Safety, comfort and dimensions of the swimming zone
4.2 Miscellaneous	Added value through extra recreation possibilities
5 Construction	
5.1 Execution	Complexity and local experience with construction method and design
5.2 Material availability	Local availability of required materials
6 Environment	
6.1 Longshore transport	Facilitation of uninterrupted longshore transport
6.2 Fabrication and transport	Ecological impact associated with logistics and prefabrication
6.3 Biodiversity	Impact on biodiversity and possibility to create new livelihoods
7 Risks	
7.1 Complexity	Risk due to design or fabrication complexity

5.1.3 Results MCA

The results of the MCA can be seen in Table 5.2

The most favourable solution according to the MCA is the artificial reef, closely followed by a combination of the reef with a submerged breakwater. An exposed nourishment, as defined in the zero-alternative seems to be the least favourable solution, mostly due to the low scores on protective qualities and maintenance requirements.

As all three options which include structures are favourable, with relatively small differences between their total scores, all three options will be considered in the detailed designs. The MCA only focuses on performance of the solutions and does not account the importance of costs. Therefore, it is only logical that the combined solution is one of the most favourable, though it is easily understood that this will the most expensive solution as well.

Table 5.2: MCA results

Criterion	Protection	Maintenance	Spatial	Recreation	Construction	Environment	Risk	Total Score
Weight factor:	4	1	4	3	3	2	1	
1: Nourishment	12	4	32	18	24	18	4	**112**
2: Artificial reef	40	13	32	27	18	22	2	**154**
3: Submerged breakwater	44	16	20	15	15	14	4	**128**
4: Combined	48	14	20	27	15	18	3	**145**

Artificial reefs come out on top due to their good spatial, recreational and environmental qualities while offering surprisingly good coastal protections as well. A solution combined with a submerged breakwater comes out as second best but will carry a much higher financial burden.

The traditional, reliable submerged breakwater is also an option worth considering, as it retains sediment well, requires minimal maintenance and is a low-risk alternative.

5.1.4 Conclusion

The MCA indicates neither a passive stance, nor a nourishment-only scenario fulfils the multidimensional requirements put forward in the durable development of Oasis beach. Financial restrictions are expected to limit the viability of a combined solution; however, this option will be considered for completeness. Please note that neither of these two structures supplies a solution for the beach section on its own, as sedimentation cannot be initiated in significant amounts due to the limited presence of sediment and narrow foreshore profile. Nourishment and an additional groyne on the western boundary will therefore always be required. The two interventions will thus be proposed in the context of nourishing by default.

5.2 Detailed solutions

The different coastal solutions are described in this section by means of an elaborated design, planning and cost estimation. The sections start with the general cost estimation strategy, which is implemented in solutions.

5.2.1 Cost estimation method

During the computation of the costs of all alternatives, the same cost estimation strategy based on Cen (2005) is performed, see Table 5.3.

Table 5.3: Cost estimation strategy according to Cen (2005)

Primary cost		
Component		**Value**
C1	Direct cost of material	Sum of elements in C1
C2	Direct cost of labour	Sum of elements in C2
C3	Direct cost of equipment	Sum of elements in C3
C4	Direct cost of support and minor materials	3% of C1+C2+C3
C5	Total direct cost	C1+C2+C3+C4
C6	Indirect cost	29% of C5
C7	Profit	20% of processing cost*
C8	Total primary cost	C5+C6+C7
Secondary cost		
Component		**Value**
P1	Temporary facilities	Sum of elements in P1
P2	Transport	Sum of elements in P2
P3	Other additional cost	Sum of elements in P3
P4	Banking	Sum of elements in P4
P5	Insurance	Sum of elements in P5
P6	Unforeseen cost	Sum of elements in P6
P7	Total secondary cost	P1+P2+P3+P4+P5+P6
P8	Total capital costs	C8+P7

* Processing costs: C2+C3+0.03(C2+C3)+0.2987(C2+C3)=1.3287(C2+C3)

Currency

Cuba makes use of two currencies: the peso Cubano (CUP) and a dollar-coupled peso convertible (CUC). The latter is mainly used in large transactions and by foreigners. The currencies have the following values per October 2018:

- €1.00 = $1.19 CUC
- $1.00 CUC = $24.00 CUP

Final figures will be supplied in euros, dollars (CUC), and pesos (CUP).

Units of currency spent today will represent a larger value in the future given that inflation persists. Stable economies have easily predictable discount rates. However, the Cuban economy is very prone to both positive and negative stimuli by foreign economies and domestic politics (Amara, Christiansen, & Dedio, 2017). These uncertainties were also identified by (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014) and subsequently the same discount value of 4% was taken. This value will not be addressed as the projected inflation rate of 4% is assumed which means a balance is found in valuation and devaluation of Cuban currency.

5.3 Zero alternative

The different alternatives are discussed by means of a detailed design, method statement and a cost estimation. As for all solutions, the basis is formed by the zero alternative, which consists of the initial nourishment and the construction of the groyne on the western boundary of the Oasis beach section, see Table 5.4. As all solutions include these measures, a separate price and schedule is indicated for them, to prevent unnecessary repetition.

Table 5.4: Design inclusion of different alternatives

Instalment/alternative	Submerged breakwater	Artificial Reef	Combined solution
Demolition	**x**	**x**	**x**
Nourishment	**x**	**x**	**x**
western groyne	**x**	**x**	**x**
Elongated western groyne	x		x
Paso Malo extension	x		x
Submerged breakwater	x		x
Artificial reef		x	x

5.3.1 Demolition

The Oasis beach in its current state is not ready to start construction. Several hard structures are present, which have reached the end of their lifetime. Two submerged breakwaters are present: One westward from the most seaward point of the Paso Malo groyne and one in the middle of the Oasis sector. The state of the first of these structures has been determined through visual observations from the Paso Malo groyne. Inspection revealed that the structures are severely worn and no longer have a sufficient wave reducing quality to fulfil their function. Apart from these problems, the required nourishment would place these structures in the shallow zone, which could cause local erosion problems and result in these structures to stick out from.

5.3.2 Design – nourishment

The second part of the zero-reference solution is the initial nourishment. The required nourishment volume was calculated to be 79,000 m^3 for achieving a minimal beach width of 40 metres, see section 1.6 and Figure 5.1. This is considerably lower than the volume estimated in 2014, which amounted to 150,000 m^3, based on a sand package thickness of 1.0 m throughout the nourishment zone (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014). Conversion of time spent on nourishment construction from 2014 to 2018 is thus done as follows:

$$T_{2018} = \frac{79}{150} * T_{2014}$$

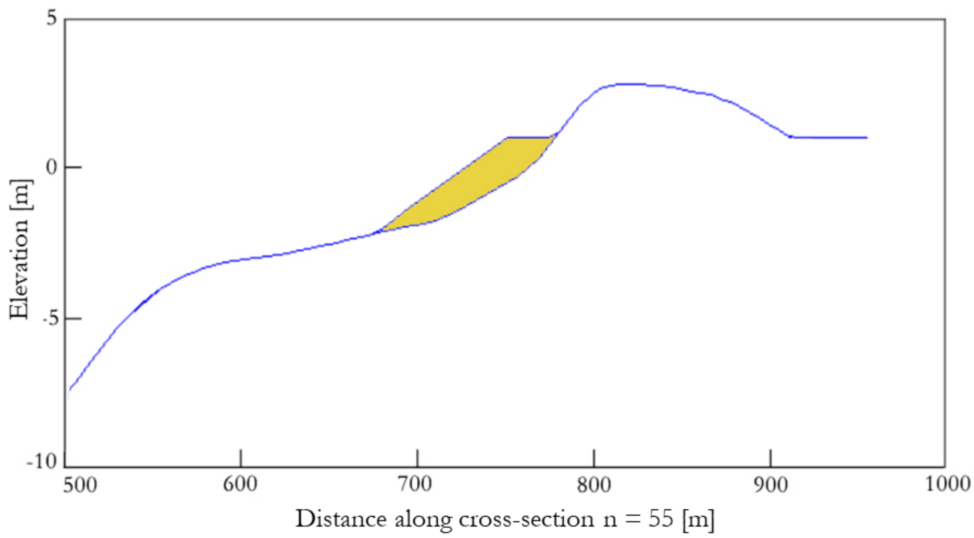


Figure 5.1: Visualisation of the nourished sand volume in the median cross-section

5.3.3 Design – western groyne

In this alternative, the groyne is fully emerged, stretching over a length of 90 metres from the dune line to the 3-metre depth contour. The offshore length of the groyne is approximately 60 metres. Including the 40 metres the Oasis beach spans, the total length of the groyne will be 90 metres, see Figure 5.2.

Availability of quarried rock is low in Cuba. Yet, there is a large surplus in concrete production capacity. No specific choice for element type will be proposed here (e.g. cubic, antifer) but dimensions for groyne layering will be provided.

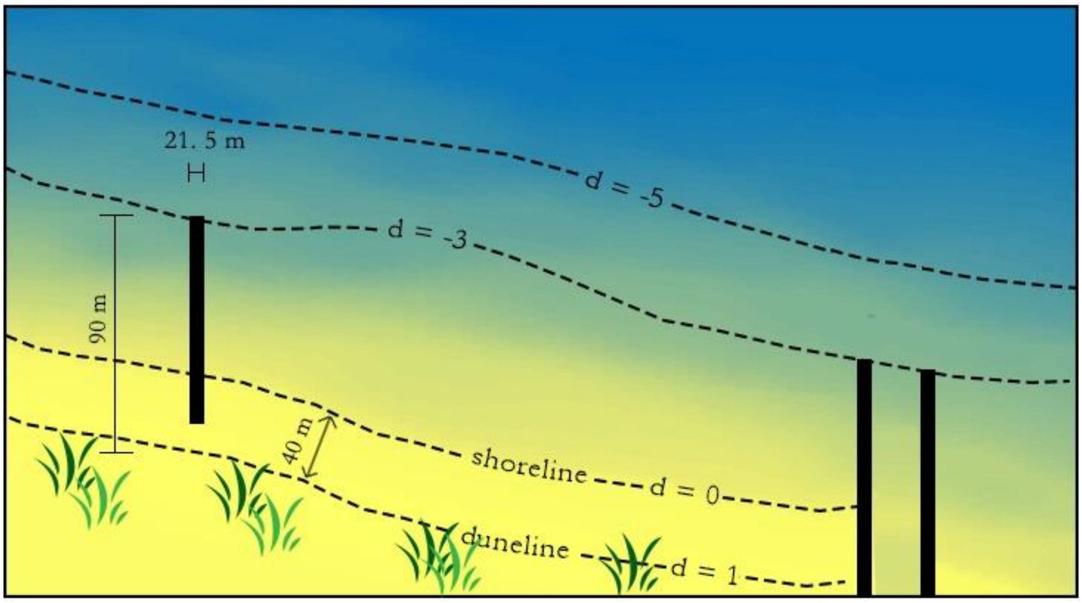


Figure 5.2: Zero-alternative plan view (not to scale)

Wave exposure

Three types of wave could reach the groyne: exposed cold front waves (NW), post-breakwater normal condition waves (NE) and waves caused by hurricane winds. Determining the maximum possible wave height imposed in these situations provides information about design requirements for the two sides of the groyne. A combined set-up of 0.71 metre as determined in hurricane Wilma conditions was an insufficiently conservative estimate. Therefore, an additional 0.5 metre of freeboard is added. A maximum wave height present around the groyne can now be determined, see the formula below.

$$H_{g,max} = \gamma * (\eta_{T,max} + \eta_{s,max} + h_{g,max})$$

With:

$H_{g,max}$	Maximum wave height at groyne	4.93	[m];
γ	Wave breaker parameter	0.8	[-];
$\eta_{T,fb}$	Additional freeboard	0.5	[m];
$\eta_{s,max}$	Maximum storm surge	0.71	[m];
$h_{g,max}$	Maximum water depth at groyne	5.0	[m]

The resulting wave height of 4.93 metres is the highest wave at the exposed western side of the groyne, based on depth-induced breaking. This is the height above MSL needed to ensure complete sheltering of Oasis beach during tropical storms from the northwest based on hurricane Wilma (2005), as indicated in the wave analysis in section 2.5.

In the presence of a submerged breakwater, the maximum wave height H_{max} is reduced to 1.20 metres as 70% wave height reduction is imposed (Section 3.2). The alternative without storm protection given Irma (2017) conditions yields H = 4.00 metres as depth-induced breaking occurs just before reaching the groyne. In short, the groyne is expected to be exposed to the wave conditions shown in Table 5.5.

Table 5.5: Significant wave height during normal-, cold front- and hurricane conditions

Conditions	H_{max} [m]
Cold front, breakwater	0.6
Cold front, exposed	2.1
Hurricane, exposed	4.00
Absolute maximum, exposed	4.93

Crest width

A 3 m crest width is adopted from (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014) as it is not regarded a critical parameter due to its sediment-blocking function and tolerance for (infrequent) damaging.

Armour stone

All following steps have been derived from the contents of 'CIE 5308 – Breakwater Design (2018)' as provided by J.P. van den Bos and H.J. Verhagen (Delft University of Technology).

Sediment entrapment is the main purpose of the western groyne. Yet, emerged parts of the structure do not need to be impermeable, the same goes for the armouring layer. This enables the design to be made partially impermeable. This was recognised in (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014).

$$\xi_s = \frac{\tan\alpha}{\sqrt{s_m}}$$

$$s_m = \frac{2\pi H_s}{gT_m^2}$$

With:

ξ_s	Irribarren parameter		[-];
α	Seaward slope angle of structure	26.6	° ;
s_m	(Fictitious) wave steepness		[-];
H_s	Significant wave height (short term)		[m];
T_m	Mean wave period		[s];
g	Gravitational acceleration	9.81	[m/s^2]

The seaward slope angle was taken to be 1:2 in the initial design implying a 26.6° angle. Significant wave heights were discussed earlier this paragraph. Mean wave periods follow from Section 2.5 and the relation:

$$T_m \approx 0.95T_p \qquad \text{(Holthuijsen, 2007)}$$

Plunging wave climate for: $\xi_s < \xi_{cr}$
Surging wave climate for: $\xi_s > \xi_{cr}$

$$\xi_{cr} = \left[\frac{c_{pl}}{c_s} P^{.31}\sqrt{\tan\alpha}\right]^{\frac{1}{P+0.5}}$$

With:

ξ_{cr}	Critical Irribarren parameter	4.25	[-];
c_{pl}	Plunging wave coefficient	7.25	[-];
c_s	Surging wave coefficient	1.05	[-];
P	Notional permeability structure	0.4	[-]

Notional permeability (P) indicates the relation between different grainsizes in subsequent layers of the groyne. Common misconception is to assume it to be indicating the ease of water passage through the structure similar to soil porosity. A value of 0.4 is commonly taken for the notional permeability. The specific gravity is based on a concrete density of 23 kN/m^3.

$$\frac{H_s}{\Delta d_{n50}} = c_{pl}P^{.18}\left(\frac{S}{\sqrt{N}}\right)^{.2}(s_m)^{.25}\sqrt{\cot\alpha}$$

With:

Δ	Specific gravity	1.30	[-];
d_{n50}	Nominal median block diameter	t.b.d.	[-];
S	Damage level	2	[-];
N	Number of waves	7.37*10^7	[-]

A standard relative density for construction concrete of 1.30 is proposed here. High-density concrete (Δ=2.0) may also be used to achieve a thinner structure but it will drive up cost. The damage level (S) depends on the nominal median block diameter which needs to be determined. Hence, finding a value for d_{n50} could be done in an iterative process. The number of waves (N) implies a timescale on which the assumed damage level must be observed. This number of waves before repairs was estimated as follows:

- Number of normal condition waves in an average year:
  - $\frac{T_{normal}-T_{coldfront}}{T_{m,normal}} = \frac{(365-16)*24*3600}{4.2} \approx 7.18 * 10^6\ waves$
- Number of cold front condition waves in an average year:
  - $\frac{T_{coldfront}}{T_{m,coldfront}} = \frac{16*24*3600}{7.3} \approx 7.18 * 10^6\ waves\ \ \approx 0.19 * 10^6\ waves$
- This totals 7.37 million waves yearly on average
- Taking the design storm of 1 in 10-year recurrence we find a total of 73.7 million waves.

$$S = \frac{A}{d_{n50}^2}$$

$$d_{n50}^2 = \left(\frac{W_{50}}{g\rho_s}\right)^{\frac{2}{3}}$$

With:

A	Erosion area in cross-section	[m^2];
W_{50}	Mean weight of armour stones	[N];
ρ_s	Density of armour stone	[kg/m^3]

High uncertainties are associated with prediction of the erosion area (A) but standardised values for S can also be used. A damage factor of 4 is reasonable considering a 1:2 slope and the possibility of intermediate repairs after extreme events. This yields d_{n50} of around 1.50 m (table 5.6). This allowance of damage is in line with (Objective 3) where it is stated that some beach erosion is allowed due to the extreme nature of tropical storms.

A layer thickness must be determined to prevent immediate exposure of the inner material after damage infliction (CIRIA, 2007) advises on this thickness using the following Formula.

$$t = nk_t d_{n50}$$

With:

t	Layer thickness	t.b.d.	[m];
n	Number of stones across layer	2	[-];
k_t	Layer coefficient	1.00	[-]

The layer coefficient was determined for concrete elements in a double layer with conventional placement as quarried material is not readily available in Cuba. The possibility to make equally sized elements implies no layer thickness reduction (k_t).

The eastern face of the groyne can be either exposed or sheltered from waves depending on the presence of an offshore submerged breakwater. The previous paragraph described the steps to determine the macro and mesoscale dimensions of a groyne. Reiteration of those steps yielded the following for the eastern face of the groyne (Table 5.6), results for the western face are included as well.

Table 5.6: Design parameters for different wave conditions

Condition	H_s [m]	T_m [s]	s_m [-]	ξ_s [-]	ξ_s [-]	Breaker type	$H_s/\Delta d_{n50}$ [-]	d_{n50} [m]	T [m]
NW exposed	4.93	6.451	4.802	0.228	4.247	Plunging	2.416	1.570	3.140
NE exposed	4	9.215	2.727	0.303	4.247	Plunging	2.097	1.467	2.934
NE sheltered	1.2	5.814	1.297	0.439	4.247	Plunging	1.7410	0.530	1.060

Underlayer

The armour concrete is placed upon a sublayer, which must not be able to wash out due to intruding waves. A d_{n50} ratio between 2.0 and 3.0 will satisfy this requirement. Again, two layers are applied and layer coefficient (k_t) equals 1.00. The subsequent concrete block size is taken to be 1/2.5 times the size of the armour layer and the resulting thickness will thus be the same fraction of the armour layer thickness. The layer is designed with the same concrete diameter throughout for ease of application. The diameter is based on the largest required armour rock diameter, which correspond to the to the condition where the groyne is exposed to waves from the northwest.

Filter layer

A filter layer must be applied, despite the relatively low porosity of concrete groynes. Crevices and seams in the first underlayer may still allow for washout of fines. The same 1/2.5 diameter reduction is applied as for the underlayer. The layer is designed with the same concrete diameter throughout for ease of application and based on the largest armour rock diameter (NW exposed).

Core

Core material can be made from nourished sand. This way, littoral transport will stop at the eastern side of the groyne under normal conditions. It is advised to use the coarser fractions of the Cayo Mono sand as its D_{50} could be too fine to keep within the groyne structure (2.3.3 Sedimentology).

Toe

In (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014) absolute stability of the groyne is guaranteed by locking it in a doubly excavated trench. The excavation of Another important aspect in the groyne design is toe stability. This section of the groyne supports the armour layer, which is only necessary for the upper part of the structure where significant wave attack takes place. The following formulas are valid for sufficiently shallow toes ($h_t/H_s < 2$).

$$\frac{H_s}{\Delta d_{n50}} = \left(0.24 * \frac{h_t}{d_{n50}} + 1.6\right) N_{od}^{.15} \qquad for\ 3 < \frac{h_t}{d_{n50}} < 25$$

$$\frac{H_s}{\Delta d_{n50}} = \left(\frac{6.2 h_t}{h} + 2\right) N_{od}^{.15} \qquad for\ 0.4 < \frac{h_t}{h} < 0.9$$

With:

h_t	Toe depth	[m];
N_{od}	Damage number(s)	[-]

The damage numbers indicate the number of displaced armour rock within a strip of breakwater with width d_{n50}. We again assume some damage has just occurred due to a hurricane, a good choice for damage number N_{od} would then be 0.5.

A toe depth of 2.5 m is assumed as a first estimate, resulting in a relative toe depth (h_t/h) of 0.5. This results in required block diameters (d_{n50} of 0.83 m for the outer layer, 0.57 m for the second layer and 0.20 m for the core layer respectively. Adapted groyne geometry, hydrodynamics and design-specific materials are described in Appendix M.

Toe cross sections

The assumed toe berm dimension ($3d_{n50}$ x $2d_{n50}$) is calculated for both conditions

- NW exposure and NE exposure yields a westward toe of 2.49 m wide and 1.66 m high and an eastward toe of 2.01 m wide and 1.34 m high.
- NW exposure and NE sheltering yields a westward toe of 2.49 m wide and 1.66 m high and eastward toe of 1.59 m wide and 1.06 m high. Given the diameter equals to the armour diameter on the eastern side (0.53 m, imposed minimum).

The cross section of the final design of the groyne is shown below.

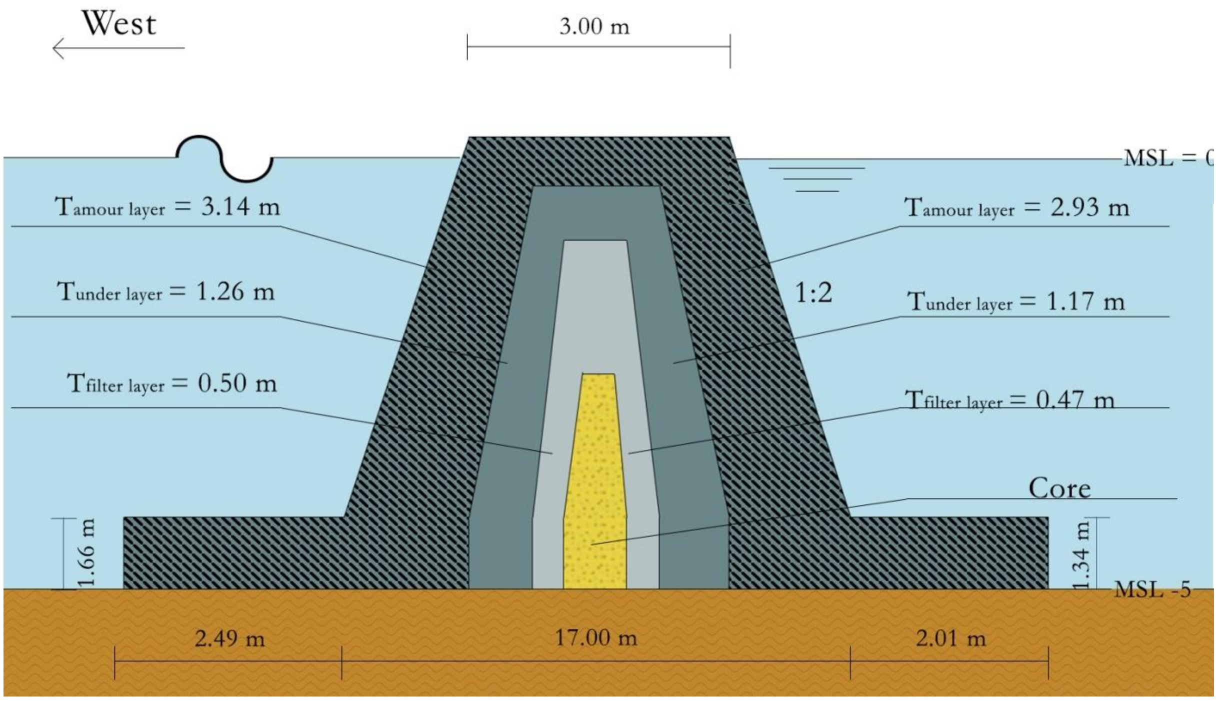


Figure 5.3: Detailed cross view of the groyne design (not to scale)

5.3.4 Project planning and cost estimation

The planning and costs of the zero alternative are discussed in this section. Gantt charts are used for a clarification of the planning and the (Cen, 2005) method is used for describing the costs, see section 5.2.1. All starting dates are based on the possible placement of an artificial reef, which is preferably done at the beginning of March.

Project planning zero alternative

The zero alternative starts with the demolition of the hard structures on Oasis beach, after which the construction of the western groyne and nourishment can take place, see the Gantt charts in figures 5.4, 5.5 and 5.6. For a clarification, the activities listed in the chards are described briefly.

Demolition activities:

Design phase:

Short deliberations about logistics and debris dumping should be done. Also, an investigation will be carried out about the way these structures were founded at the time.

Preparation phase:

And entrance road for vehicles and crew utilities (e.g. a lavatory) should be placed. Permits and contracts need to be arranged for here.

Demolition phase:

All old structures on the beachfront will be broken down and removed. These are: two small bunkers, one 10-metre groyne, a steel boat frame, a small concrete pier and three blocks of concrete adjacent to the Paso Malo groyne. Debris will be transported to either a buyer or dump.

Cleaning:

Present litter will be removed alongside residual rubble from the demolition works.

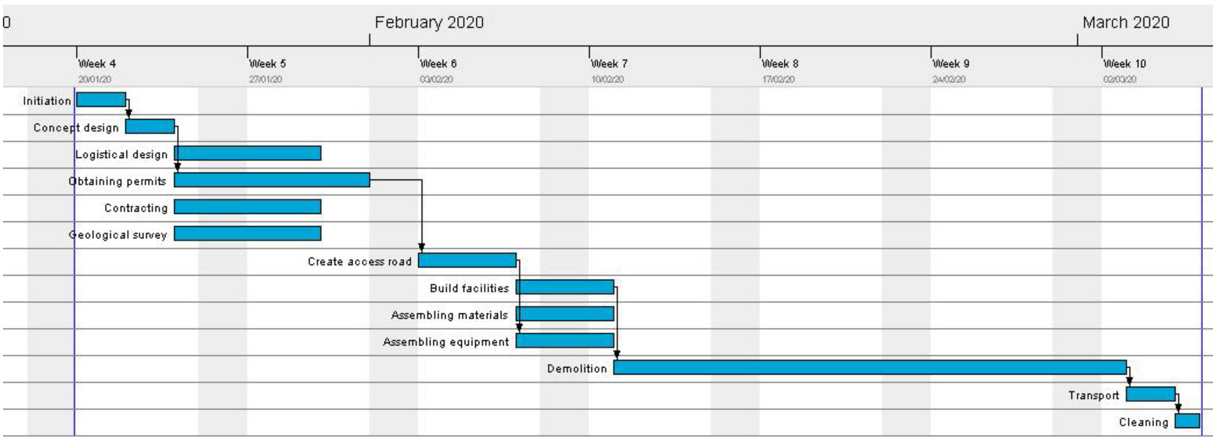


Figure 5.4: Detailed demolition method statement

Groyne construction activities:

Design phase:

Longshore transport was only shortly assessed in the Durable Development of Oasis Beach. Hence, it is advised that a more detailed simulation is carried out in the development of the final design of the groyne. A timeframe of five months was assigned to design the western groyne.

Preparation phase:

Permit and contract acquisition is carried out while a more detailed survey of the bathymetry and soil composition is done. Early identification of e.g. pockets of weaker calcareous rock, which can be found in northern Cuba, could prevent damage and capital destruction.

Construction phase:

The groyne will be realised by two modes of construction: offshore block deposition by barges and nearshore placement of concrete. Three quarters of the works will be done offshore, and onshore works will be carried out simultaneously.

Inspection:

A short inspection should prove technically sound placement of groyne layers and reliability of individual block elements.

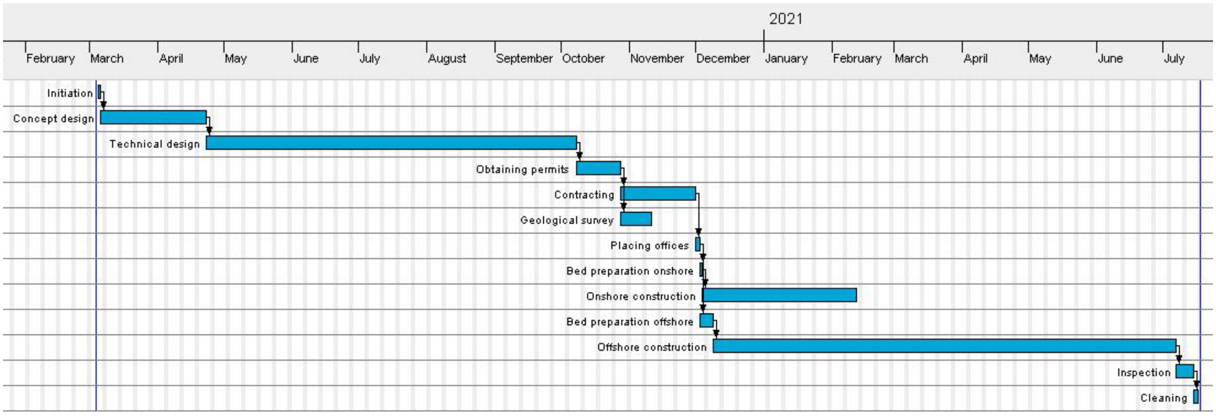


Figure 5.5: Detailed western groyne method statement

Nourishment activities:

Design phase:

Verification of the proposed nourishment volume should suffice as a final design for the works.

Preparation phase:

Preparations consist of placement of personnel facilities and the transport pipeline.

Construction phase:

Four persons will be operating the tugboat and two will do on-land redistribution of sand in bulldozers. The starting date of nourishment activity is based on the timing of reef placement as described in and completion of the groyne.

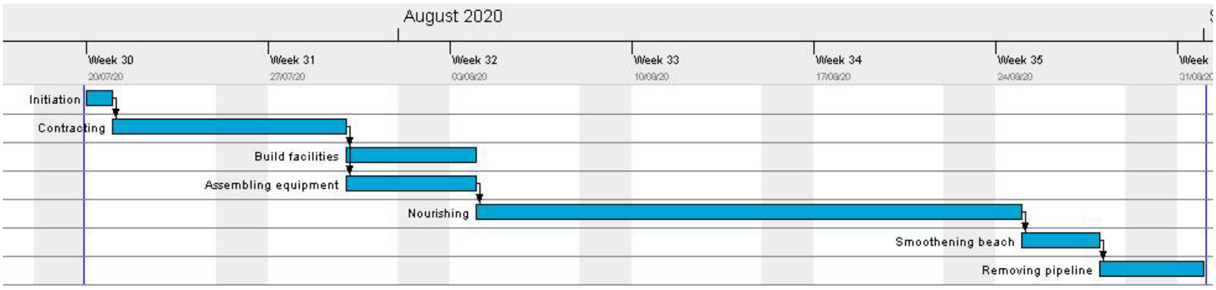


Figure 5.6: Detailed nourishment method statement

Cost estimation zero alternative

Independently, the costs of the demolition, western groyne and nourishment are shortly discussed. In Appendix N, a more elaborated overview is given.

Regarding the demolition schedule of 2014, no essential changes were made as it concerns the same structures that must be removed. A minor fix did result in a lower total cost value. The starting date of demolition is based on the timing of reef placement as described in Section 3.3.2. The demolition cost estimation is shown in Table 5.7.

Table 5.7: Demolition cost estimation

Oasis structure demolition 1			
1. Time estimation:		2. Number of employees	
1.1 Total duration:	34 days	per phase:	
1.1.1 Design phase:	5 days	4 persons	
1.1.2 Preparation phase:	12 days	10 persons	
1.1.3 Construction phase:	15 days	10 persons	
1.1.4 Cleaning	2 days	4 persons	
1.2 Daily hours of labour:	8 hours		
1.3 Start date:	17-12-2019		
1.4 Delivery date:	11-2-2020		
1.5 Project lifetime:	-		
3. Financial summary		4. Equipment	
3.1 Total project cost:		4.1 Crane	
	$ 270,132.24 CUP	4.2 Hammer	
	$ 11,255.51 CUC	4.3 Bulldozer	
	€ 9,454.63 EUR		
Exchange rate CUC/CUP:	1 CUC = 24 CUP	1 CUC = €0.84	

The construction of the western groyne in the zero alternative can start after the demolitions of the hard structures. In table 5.8 a cost estimation is given.

Table 5.8: Western groyne cost estimation

Western groyne construction - not sheltered from NE			
1. Time estimation:		2. Number of employees	
1.1 Total duration:	372 days	per phase:	
1.1.1 Design phase:	158 days	4 persons	
1.1.2 Preparation phase:	27 days	10 persons	
1.1.3 Construction phase:	180 days	10 persons	
1.1.4 Inspection:	7 days	2 persons	
1.2 Daily hours of labour:	8 hours		
1.3 Start date:	13-2-2020		
1.4 Delivery date:	16-7-2021		
1.5 Project lifetime:	30 years		
1.6 Maintenance lifetime:	30 years		
3. Financial summary		4. Equipment	
3.1 Total project cost:		4.1 Barge	
	$ 7,031,218.80 CUP	4.2 Truck with crane	
	$ 292,967.45 CUC		
	€ 246,092.66 EUR		
Exchange rate CUC/CUP	1 CUC = 24 CUP	1 CUC = €0.84	

Nourishment must be executed after instalment of the groyne to prevent unnecessary longshore losses. The actual volume of 79,000 m^3 (See Section 5.3.2) was found after adding 10% direct-loss volume and 10% for nourishing with finer grainsizes.

Table 5.9: Nourishment cost estimation

Oasis beach nourishment			
1. Time estimation:		2. Number of employees	
1.1 Total duration:	32 days	per phase:	
1.1.1 Design phase:	5 days	2 persons	
1.1.2 Preparation phase:	12 days	4 persons	
1.1.3 Construction phase:	15 days	6 persons	
1.2 Daily hours of labour:	8 hours		
1.3 Start date:	19-7-2021		
1.4 Delivery date:	31-8-2021		
1.5 Project lifetime:	5 years		
3. Financial summary		4. Equipment	
3.1 Total project cost:		4.1 Tugboat	
	$ 226,290.72 CUP	4.2 Pipeline	
	$ 9428.78 CUC	Cayo Mono borrowing area	
	€ 7,920.18 EUR	Sand D50 = 60 µm	
Exchange rate CUC/CUP:	1 CUC = 24 CUP	1 CUC = €0.84	

5.4 Submerged breakwater alternative

The second alternative design is the submerged breakwater. This traditional design dissipates wave energy and reduces sediment transport by inducing depth-induced breaking further offshore, to prevent the wave turbulence from picking up sediment nearshore. This subsection describes the detailed design of the elongated western groyne and Paso Malo and the submerged breakwater, see Table 5.10.

Table 5.10: Design inclusion of different alternatives

Instalment/alternative	Submerged breakwater	Artificial Reef	Combined solution
Demolition	**x**	x	x
Nourishment	**x**	x	x
western groyne	**x**	x	x
Elongated western groyne	**x**		x
Paso Malo extension	**x**		x
Submerged breakwater	**x**		x
Artificial reef		x	x

5.4.1 Design – western groyne

The western groyne in this alternative differs somewhat in dimensions with respect to the zero alternative. During calibration of the submerged breakwater alternative in which the groyne reached from the dunes to the 3-metre depth contour, a significant washout of sediment seaward of the groyne was observed when west-north-western storm conditions (hurricane Irma) were used as in the model.

To prevent this, the groyne will need to be lengthened to the position of the (proposed) submerged breakwater, which is at MSL-5.0 m (Section 3.3.2). This results in an offshore groyne length of 105 m metres and a total length of 135 m metres when beach embedment is added.

The extension of the groyne to the submerged breakwater has therefore been implemented in the submerged breakwater alternative. This will mean that the groyne will reach to the MSL-5.0 metre depth contour in that design alternative. The dimensions of this elongation will be discussed in below. A plan view for this design is shown in Figure 5.7. Furthermore, as breakwater is constructed first, see the Project planning in this section, it retrieves shelter during exploitation phase. Therefore, the used d_{n50} is reduced slightly, see Figure 5.8.

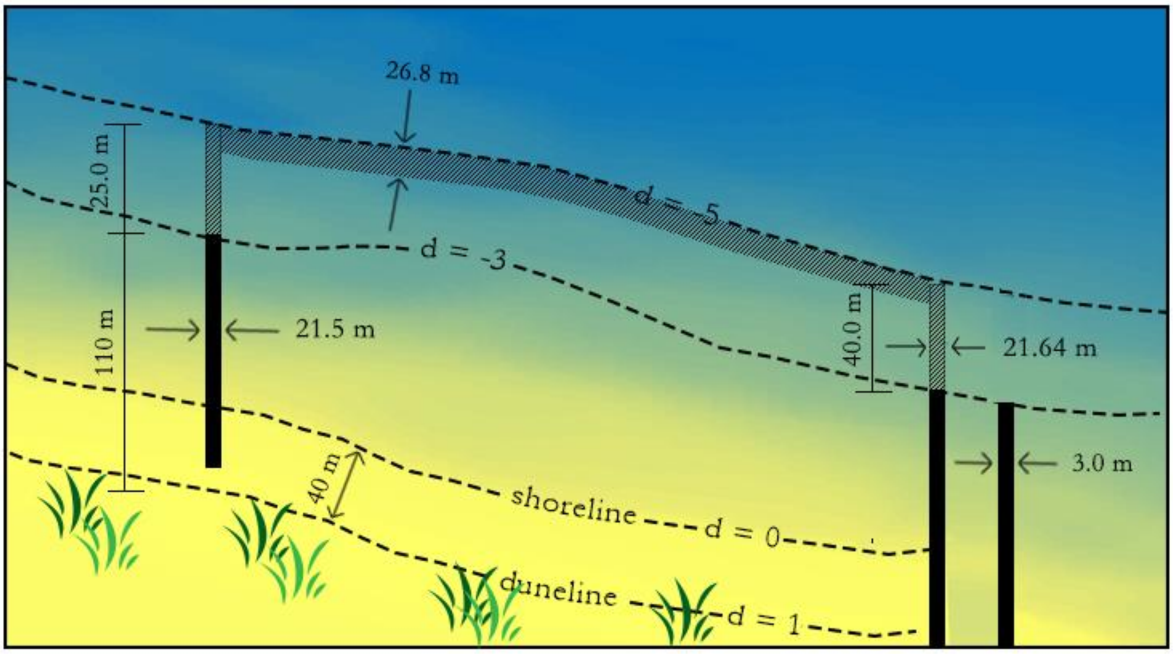


Figure 5.7: Submerged breakwater alternative plan view (not to scale)

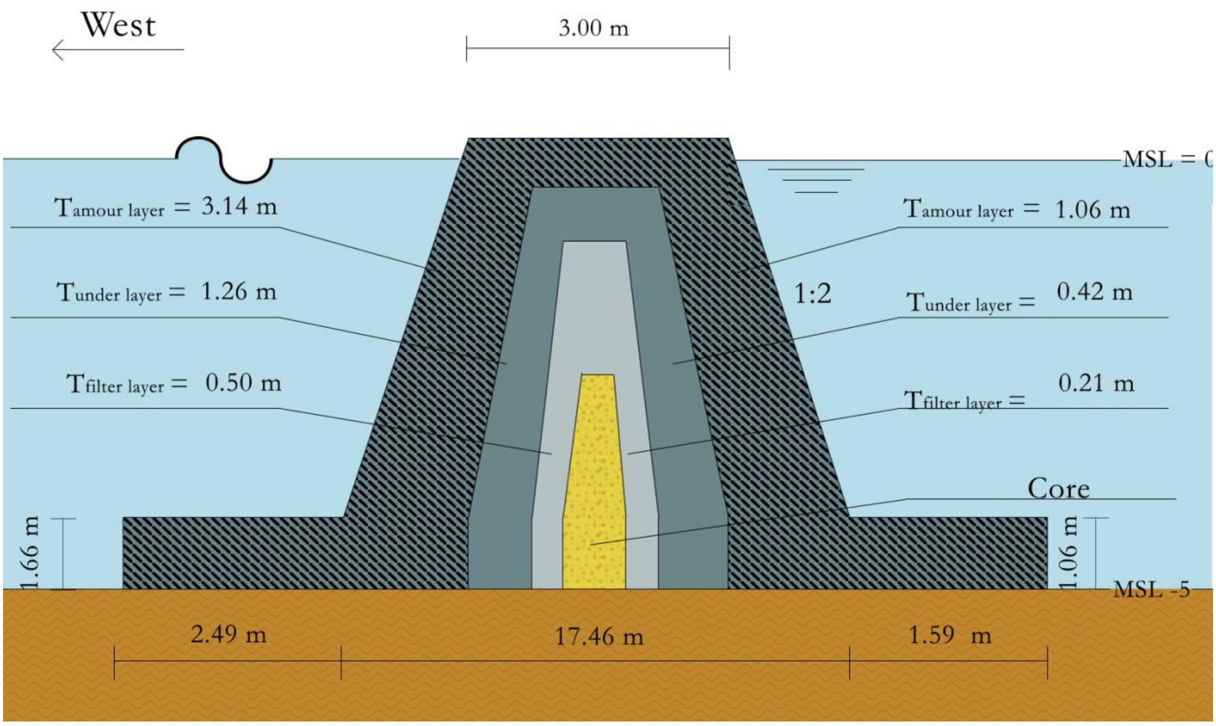


Figure 5.8: Detailed cross view of the elongated groyne design (not to scale)

5.4.2 Design – Submerged breakwater

All of the following procedures are borrowed from the Rock Manual (CIRIA, 2007) and the academic lecture notes (van den Bos & Verhagen, 2018)

An important parameter in designing breakwaters in general is the freeboard (R_c), i.e. the crest elevation above the design water level. In case of a submerged breakwater the freeboard is negatively valued. The concept design (Section 3.3.2) assumed a freeboard of -0.3 m MSL.

The initial design delineates the overall position, height and length of the offshore submerged breakwater (See Section 3.3.2). Modelling exercises proved that these dimensions indeed fulfil their required characteristics regarding wave breaking and sheltering effects (See Appendix I). The last macro dimension that needs verification is the crest width.

A maximum wave height present around the groyne can now be determined as follows.

$$H_{g,max} = \gamma * (\eta_{T,max} + \eta_{s,max} + h_{g,max})$$

With:

$H_{g,max}$	Maximum wave height at groyne	4.93	[m];
γ	Wave breaker parameter	0.8	[-];
$\eta_{T,max}$	Maximum positive tidal elevation	0.45	[m];
$\eta_{s,max}$	Maximum storm surge	0.71	[m];
$h_{g,max}$	Maximum water depth at groyne	5.0	[m]

The parameter that governs the thicknesses of all layers in the breakwater is the median armour stone size (d_{n50}). A good first estimate for the armour stone size may be found from assuming statically stable conditions and damage initiation at the same time. Rock Manual (2007) provides advisory values of armour stone size per allowable damage through the stability number (N_s) which is 4.0 for the situation sketched here. The stability number is represented by the next formula.

$$N_s = \frac{H_{g,max}}{\Delta d_{n50}}$$

Lower stability numbers indicate less damage to the structure through the stone size that is applied on the slopes. This yields a median armour stone diameter of 0.95 m as a first estimate.

Although the calculation scheme for the submerged breakwater dimensions has been quite similar to that of the western groyne (Section 5.3.3) thus far, some economising may be done with respect to the micro dimensions.

Permanently submerged breakwaters experience less wave forcing than their emerged counterparts as much of the wave energy passes overhead. This allows for a reduction in armour stone size which can save up to 50% in weight of armour stone. The following formula shows the calculation of this reduction factor.

$$R_{dn50} = \frac{1}{1.25 - 4.8R_p^*} \quad , \; for\ 0 < R_p^* < 0.052$$

And:

$$R_p^* = \frac{R_c}{H_s}\sqrt{\frac{s_m}{2\pi}}$$

With:

R_C	breakwater freeboard	[m]
s_m	fictitious wave steepness	[-]

Refer to Section 5.3.3 for calculation of the wave steepness (s_m). No significant reduction can be achieved the reduction factor is practically 1.0. Crest stability regarding armour stone size is verified through the next formula below. The initial estimate of 0.95 m is inserted in the right-hand side of the equation. The left part of the equation represents the stability number (N_s), refer to the previous formula for this. The right-hand side should thus amount to a value of 4.0 or smaller to ensure crest stability.

Values for A, B and C are specified in the Rock Manual for different scenarios. Here we assume instability on the back slope due to breaking tropical storm waves dissipating their energy right after the breakwater crest. Corresponding values for the coefficients are 2.575, -0.5400 and 0.1150 respectively.

$$\frac{H_s}{\Delta d_{n50}} = A + B * \frac{R_c}{d_{n50}} + C\left(\frac{R_c}{d_{n50}}\right)^2$$

With:

A, B and C	coefficients for damage initiation	[-]

The above results in a stability number of 2.76. This confirms crest stability in tropical storm scenarios.

According to Van den Bos & Verhagen (2018) short slopes are preferred on breakwaters that experience heavy storm attack. This is due to slight settlement of stones placed on the slopes whereas the flat crest section does not subside. A gap subsequently forms at the transition from slope to crest. Applying less units (steeper slope) diminishes this effect. A maximum of 20 block units is proposed, this is of no concern for the Oasis beach breakwater design as blocks of 0.95 m are applied at around -5 m MSL.

Both the fore slope and backslope are chosen to be equal due to the possibility of heavy wave action on either side. The prefabrication of concrete elements allows for a somewhat steep slope of 1:1.5.

The crest width proved very prolific in wave breaking as can be seen from modelling results, Appendix I. Also, the design strategy based on (Dattatri, Raman, & Shankar, 1978) is found to be more accurate for wide crested submerged breakwaters than the indicative table values found in Rock Manual. A width of 10 m is thus pertained.

Layer thicknesses are designed in the same manner as in Section 5.3.3. Low permeability is required as the submerged breakwater will be placed just on the edge of the active zone. A rock shape factor is again not necessary as concrete elements are used. The same diameter reduction ratio of subsequent layers (2.5) is applied to find each respective layer thickness. Layer thicknesses are found to be as follows:

- Armour layer: 1.9 m $D_{n50} = 0.95$ m
- Underlayer: 0.76 m $D_{n50} = 0.38$ m
- Filter layer: 0.30 m $D_{n50} = 0.15$ m

Excavation of a double trench (0.5 m) in the bedrock along the Oasis beach section was not adopted from (de Boer, Poelhekke, Schlepers, & Vrolijk, 2014). Instead, similar to the design of the groyne, a toe design is based on a somewhat smaller toe median rock size. A first estimate of d_{n50} is 0.75 m. Now, we find a relative toe depth (h_t/h) of 0.7. The same calculation can be used as for the groyne design and we find a final $d_{n50} = 0.96$ m. Using this diameter, we find a stability number (Ns) of 3.94, just on the safe side of the imposed value of 4.0. The newly found median diameter is roughly the same as the diameter of the armour material. The toe dimensions are thus:

- Toe height ($2d_{n50}$): 1.93 m
- Toe width ($3d_{n50}$): 2.89 m
- Toe cross section: 5.57 m^2

Figure 5.9 shows the layout of the submerged breakwater.

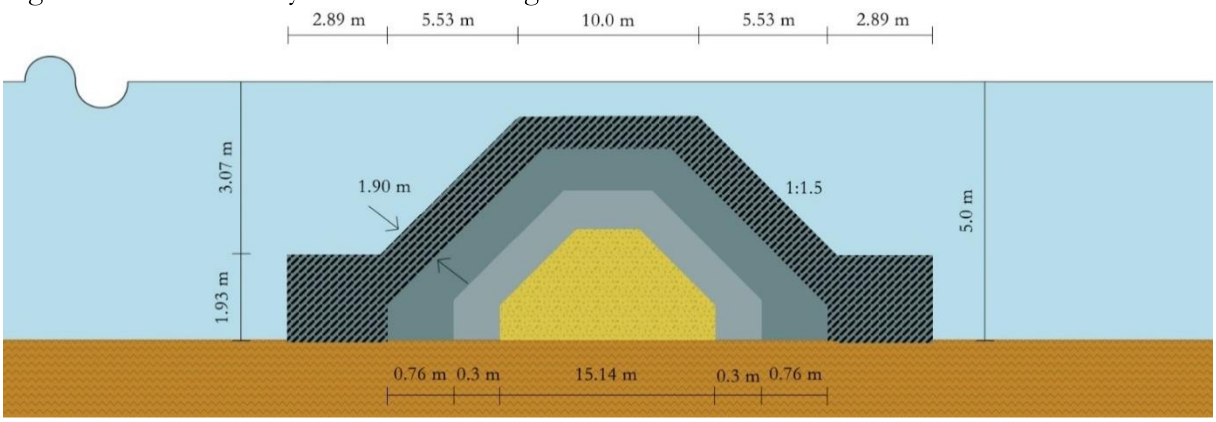


Figure 5.9: Detailed design of the submerged breakwater (not to scale)

5.4.3 Design – Paso Malo extension

Part of the design of the submerged breakwater is the inclusion of the extended Paso Malo channel to a depth of -5 m. As the groyne and Paso Malo channel have the same governing hydrodynamic conditions, the design can be similar. The only difference is found in orientation. Whereas the western groyne is dimensioned with the sea boundary at the West side, the extension of the Paso Malo channel has a sea boundary at the East side. As the characteristic at both boundaries are similar, only the dimensions of the western groyne have to be mirrored to obtain the detailed design of the extended Paso Malo channel, see figure 5.10.

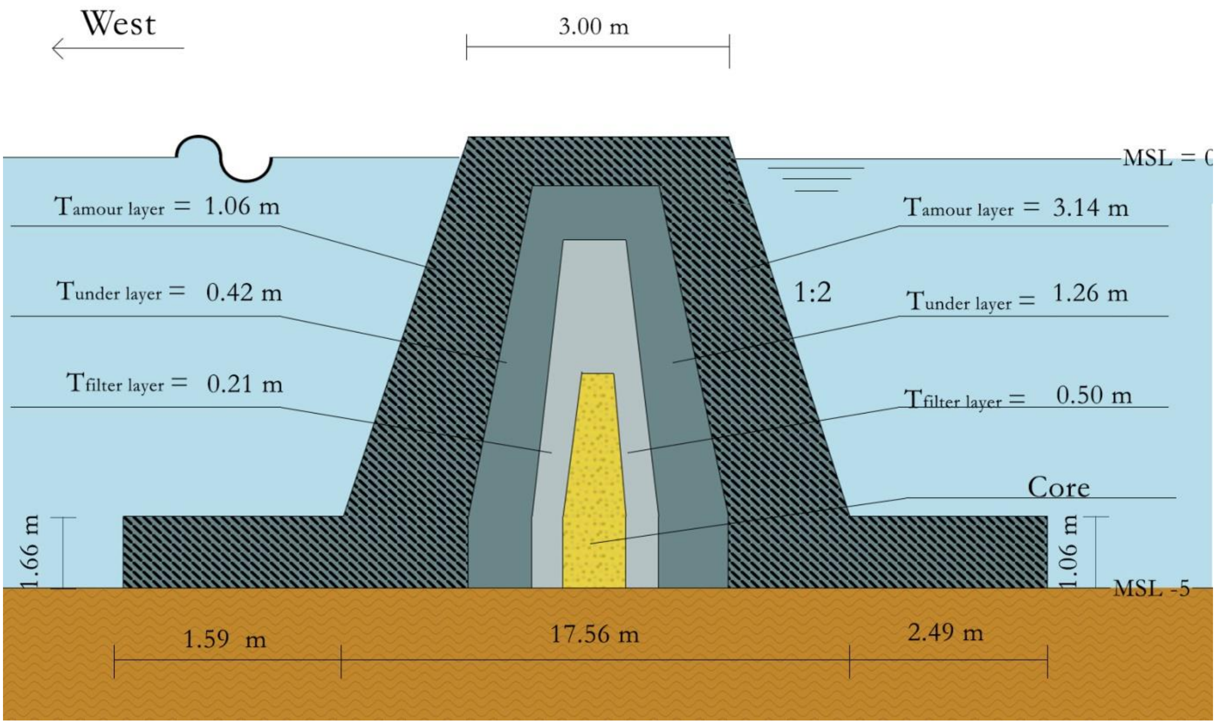


Figure 5.10: Detailed design of the Paso Malo extension (not to scale)

5.4.4 Project planning and cost estimation

The planning and costs of the submerged breakwater alternative are discussed in this section. Gantt charts are used for a clarification of the planning whereas the (Cen, 2005) method is used for describing the costs, as previously indicated in section 5.2.1.

Project planning submerged breakwater alternative

The execution starts with the construction of the submerged breakwater and Paso Malo extension, the construction of the western groyne is started, see the Gantt chart in figure 5.11 for an overview. For a clarification, the activities listed in the charts are described briefly.

<u>Submerged breakwater and Paso Malo activities:</u>

Design phase:

The first design should include a small section about repairs of the Paso Malo groyne tip. The design conditions for the submerged breakwater were the focus of this report. Detailed models were run and performance of the structure at -5 MSL is thoroughly quantified. The technical design should thus be more concentrated on the smaller dimensions (layering, elements) to obtain a more detailed design.

Preparation phase:

Permit and contract acquisition are followed by an extra bathymetric study to ensure a sufficiently stable topography along the 800-metre section. Office placement is done simultaneously and needed in case of official visits and construction monitoring by engineers. Finally, all materials can be gathered and stored just west of the beach. The sand core can be constructed first (bed preparation) as no active sediment transport takes place at -5 m MSL.

Construction phase:

Construction should be carried out in no more than 14 months based on the 40-hour, 6-day workweek. Paso Malo Groyne extension will be done at the final stage when the western part of the breakwater is under construction some 700 metres to the west.

Inspection:
A short visual inspection should prove technically sound placement of breakwater layers and reliability of individual block elements.

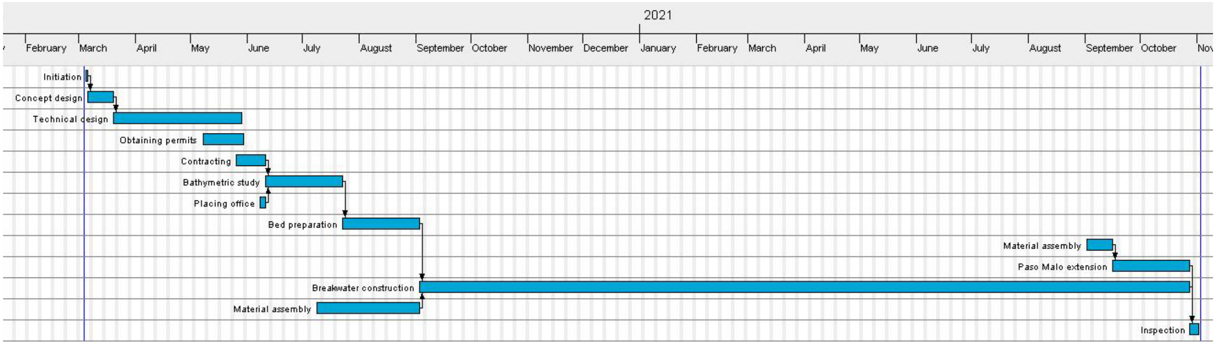


Figure 5.11: Detailed submerged breakwater method statement

Groyne construction planning is identical to the one described in Section 5.3.3. More personnel are hired to achieve the same delivery date.

Cost estimation of submerged breakwater alternative

A cost overview of the submerged breakwater and Paso Malo extension and groyne are described in the tables below. For a more comprehensive overview, reference is made to Appendix N.

Table 5.11: Cost estimation of the submerged breakwater and the Paso Malo extension

Submerged breakwater		
1. Time estimation:		2. Number of employees
1.1 Total duration:	433 days	per phase:
1.1.1 Design phase:	60 days	6 persons
1.1.2 Preparation phase:	30 days	10 persons
1.1.3 Construction phase:	340 days	25 persons
1.1.4 Inspection	3 days	4 persons
1.2 Daily hours of labour:	8 hours	
1.3 Start date:	5-3-2020	
1.4 Delivery date:	1-11-2021	
1.5 Project lifetime:	30 years	
3. Financial summary		4. Equipment
3.1 Total project cost:		4.1 Tugboat
	$ 37,778,816 CUP	4.2 Pipeline
	$ 1,574,117 CUC	4.3 Barge
	€ 1,322,259 EUR	
Exchange rate CUC/CUP:	1 CUC = 24 CUP	1 CUC = €0.84

Table 5.12: Cost estimation western groyne

Western groyne construction - sheltered from NE		
1. Time estimation:		2. Number of employees
1.1 Total duration:	356 days	per phase:
1.1.1 Design phase:	158 days	4 persons
1.1.2 Preparation phase:	24 days	10 persons
1.1.3 Construction phase:	168 days	10 persons
1.1.4 Inspection:	7 days	2 persons
1.2 Daily hours of labour:	8 hours	
1.3 Start date:	5-3-2020	
1.4 Delivery date:	16-7-2021	
1.5 Project lifetime:	30 years	
1.6 Maintenance lifetime:	30 years	
3. Financial summary		4. Equipment
3.1 Total project cost:		4.1 Barge
	$ 6,508,851.60 CUP	4.2 Truck with crane
	$ 271,202.15 CUC	
	€ 227,809.81 EUR	
Exchange rate CUC/CUP	1 CUC = 24 CUP	1 CUC = €0.84

5.5 Artificial reef alternative

The artificial reef alternative differs significantly from the breakwater alternative but is based on the same principles, namely, the dissipation of wave energy before sediment can be stirred up. The dissipation of wave energy in the reef is caused by both depth-induced breaking (which is the case for the offshore breakwater), but also by friction. This section provides a detailed design of the artificial reef proposed. A plan view of this solution is shown in Figure 5.13, The plan view also shows a layout of the positioning of the concrete elements.

Table 5.13: Design inclusion of different alternatives

Instalment/alternative	Submerged breakwater	Artificial Reef	Combined solution
Demolition	x	**x**	x
Nourishment	x	**x**	x
western groyne	x	**x**	x
Elongated western groyne	x		x
Paso Malo extension	x		x
Submerged breakwater	x		x
Artificial reef		**x**	x

5.5.1 Design – Artificial reef

Modelling results showed promising results for the initial artificial reef design for combatting erosion in normal conditions and during cold fronts (Appendix I). The results showed somewhat less successful wave dissipation in hurricane conditions. As the erosion even in these cases was limited, these the initial design will thus not be re-assessed with respect to positioning, volume and element dimensions and a combined solution with the submerged breakwater will be put forward.

Hard bottom conditions where compressive and tensile forces are applied on Reef Ball ™ elements require anchoring. No extreme vertical displacement is expected due to the shallow water column above the Goliath Balls™. Fibreglass rebar spikes are the best choice for this kind of situation. It is decided to anchor the entire periphery of the reef at Oasis beach as the highest intensities of incoming wave action and secondary currents apply to the outer rows of elements. The six outer 'column' elements (See Figure 5.12) will be fixated too to prevent any shore-parallel movement of elements. Maximum and efficient individual stability is reach in with the application of four rebar spikes per element. This brings the total number of required spikes to 3224. Elements can later be interconnected to form a grid with higher stiffness if found necessary.

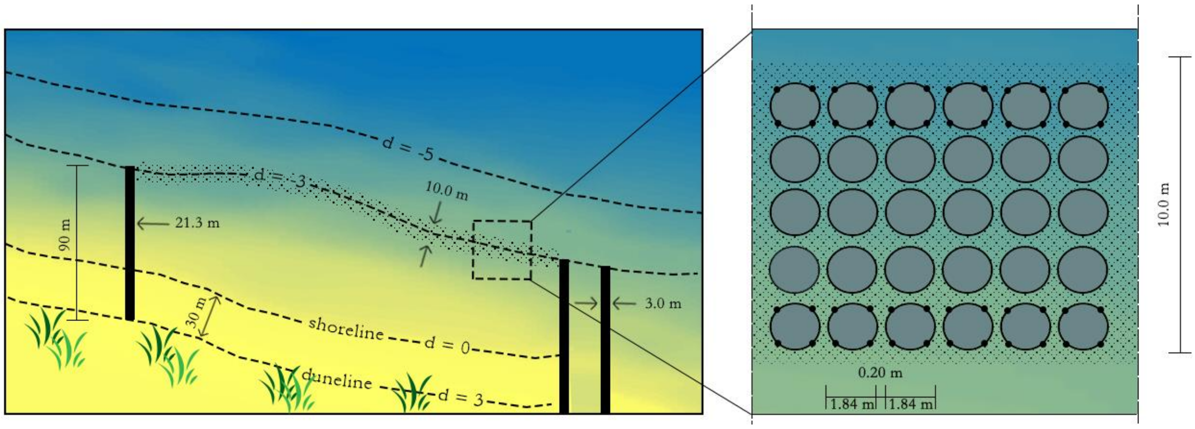


Figure 5.12: Top view of the artificial reef (right) with a detail specifying the placement of the Reef Balls (left)

Four PVC tubes are cast at angle of 45° into the substrate during Reef Ball ™ production. Specialized drills are subsequently used to create four holes in the bedrock where the element is designed to be placed. Reef deployment divers use pneumatic hammers to insert the fibreglass rods (through the element punctures) right after submerging each element. A photo of this process can be found in Appendix I.

Coral juveniles must be collected within 45 km of Oasis beach and host a variety of species with a preference for Acropora and M. Annularis.

5.5.2 Project planning and cost estimation

Project planning – artificial reef:

A high precision planning was set, based on the real-life experiences documented in (The Reef Ball Foundation, 2008). All measures of time-consumption were taken from this extensive guide to repairing or creating artificial reefs. Activities involved in reef construction are deemed not to be as transparent as the preparational works and will thus be described in more detail.

Design phase

Reef design will have to be approached in a multidisciplinary way. The effects of e.g. wave forcing, turbulence, friction and wave attenuation on sediment transport processes will need assessment and calibration by (two) hydraulic engineers. Site selection will be a joint effort with two bio-marine engineers. These engineers oversee water quality assessment, coral selection and planting strategy. This entire process is thought to take 60 workdays.

Preparation

Production time of Reef Balls ™ in Havana is not accounted for as it involves a continuous process that will not inhibit execution speed. Delivery is also deemed to be larger than pace of element deployment and hence not relevant for preparational activities. The initiation of production and delivery of the first batch is set at 31 days to reach 28-day compressive strength and deliver the first few batches. Moreover, coral saplings must be cultured or collected on a nearby reef (within 48 kilometres). One day is assumed to be lost per 5 days of work.

In (Fabi, Scarcella, & Spagnolo) it is advised that deployment of reef units starts during periods of low macroalgal activity. Furthermore, in the scope of this project, it is preferred to initiate deployment outside of tourist high-season (November-February) and peak storm season

(September-October, See Section 2.4.3). The time of year that complies best with these three preferences is right after the peak in foreign visits to Varadero, at the start of March. To ensure successful establishment of coral though, sapling insertion will start 40 days after substrate deployment. Reef Ball ™ submersion can be executed without a barge using 'internal bladders' (See Appendix I). Transport, submersion and placement can begin once the elements are present on the beachfront. Flotational placement is assumed to take one hour per unit per crew (4 snorkel workers and 2 onshore per snorkel crew, See Appendix I). This amounts to 132 days of work using 2 crews and adding 5% uncertainty due to bad visibility, erratic sea conditions or flawed installation.

Macroalgal activity was observed to be low on the Oasis nearshore and thus not considered to be of any influence on the schedule. Furthermore, relatively calm conditions at sea (See Section 2.4.1) allow for the use of coral tables (Appendix L). One of these pontoons provides a workplace for one coral placement squad with a crew of 8 consisting of:

- Table boss
- Wet hand coral handler
- Dry hand coral handler
- Five divers

Five well-instructed and experienced divers can plant up to 500 colonies daily with coral juveniles, which cost less than $1.00 on average. The Oasis beach reef makes use of 10 hermatypic coral fragments (juveniles) per submerged Reef Ball ™. This amounts to a total of 20,000 fragments to be planted. We assume the employment of 10 slightly inexperienced divers (2 crews) working at 80% of potential capacity for five full days per week (which is possible at 'snorkelling depth', which is a reasonable assumption, as the reef will be installed at a depth of 3.0 metres). This yields 800 coral plants per day and a total planting duration of 28 days assuming 5% inactivity due to unsuitable situations such as erratic seas, insufficient dissolved oxygen (< 4.5 mg/L, < 375 Oxigen Reduction Potential) or unforeseeable events. Four days will be assigned to subsequent round-up activities.

The Gantt chart below shows the entire conceptual planning of the reef construction. The red bar indicates the design phase of the reef (4 engineers). Production and delivery of the elements commences at the end of the design phase. Forty days of hydrolysation follow overlappingly by the initiation of Reef Ball ™ fixation. The critical path is found at the coral planting stage, which will not begin before successful installation of all substrate units. Here, a crew of 16 must undertake a quick succession of different skilful activities in just over a month.

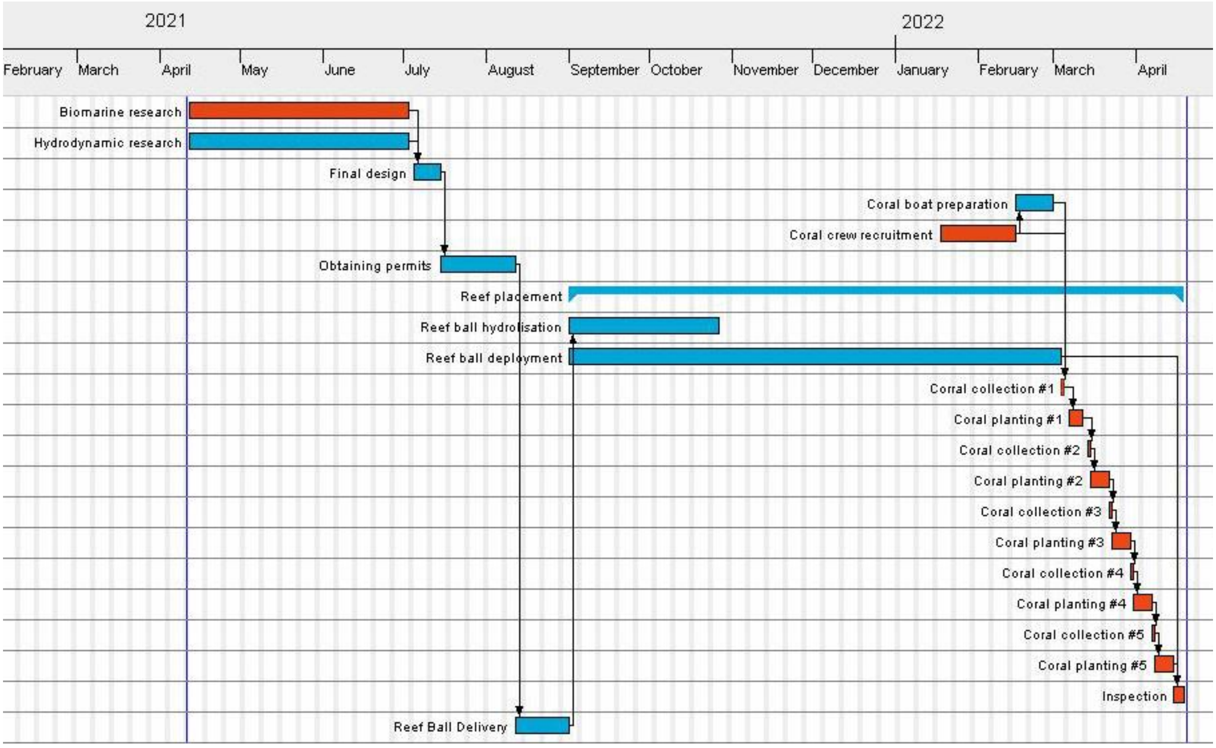


Figure 5.13: Detailed artifical reef method statement

Maintenance works will start directly after placement of the very first coral plug. Rapid tissue necrosis (RTN) or epoxy failure will be expressed in the first 48 hours after deployment. RTN or epoxy failure may be resolved within the project schedule. More natural fatalities (e.g. predators, sedimentation) will start to show weeks to months afterwards and should not be interfered with unless passiveness has severe implications for a large part of the reef.

Adding the time spent on activities preceding reef placement (demolition, groyne and nourishment) we find a total project duration of 266 working days running from 12/04/21 to 18/04/22.

Cost estimation – Artificial reef

In Table 5.14, the cost estimation of the artificial reef alternative is displayed. As already discusses, it can be noted that the final costs of this alternative are significant lower than the submerged breakwater.

Table 5.14: Artificial reef cost estimation

Artificial reef		
1. Time estimation:		2. Number of employees
1.1 Total duration (overlap):	224 days	per phase:
1.1.1 Design phase:	60 days	4 persons
1.1.2 Preparation phase:	52 days	20 persons
1.1.3 Construction phase:	164 days	28 persons
1.1.4 Inspection:	2 days	8 persons
1.2 Daily hours of labour:	8 hours	
1.3 Start date:	7-6-2021	
1.4 Delivery date:	15-4-2022	
1.5 Project lifetime:	30 years	
1.6 Maintenance lifetime:	Indefinite	
3. Financial summary		4. Equipment
3.1 Total project cost:		4.1 Hammer
	$ 14,323,726.32 CUP	4.2 Crane
	$ 596,821.93 CUC	4.3 Bulldozer
	€ 501,330.42 EUR	4.4 Truck
		4.5 Coral boat
		4.5 Coral pontoon (2x)
3.3 Exchange rate CUC/CUP	1 CUC = 24 CUP	1 CUC = €0.84

5.6 Combined solution

The fourth proposed solution is the combination of a submerged breakwater and an artificial reef, see Table 5.15. Although this combination of solutions is the most expensive, it is by far the most resistant against hurricanes and could therefore still be an interesting option. During normal and cold front wave attack the combination of the breakwater and coral reef does not provide significant additional protection, as shown in section 4.1.6.

Table 5.15: Design inclusion of different alternatives

Instalment/alternative	Submerged breakwater	Artificial Reef	Combined solution
Demolition	x	x	**x**
Nourishment	x	x	**x**
western groyne	x	x	**x**
Elongated western groyne	x		**x**
Elongated Paso Malo	x		**x**
Submerged breakwater	x		**x**
Artificial reef		x	**x**

5.6.1 Design – Combined solution

A plan overview of the combined solution is given in Figure 5.14. As can be noted, it consists out of the exact implementation of both previous described solutions. Therefore, reference is made to sections 5.3, 5.4 and 5.5 for the detailing process.

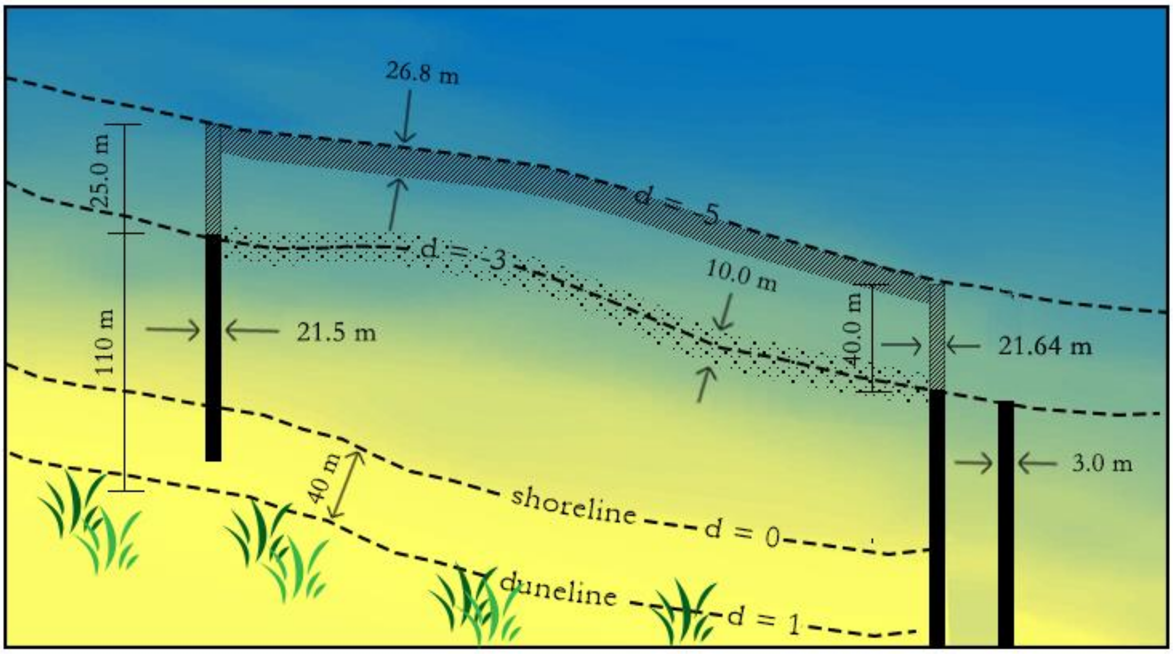


Figure 5.14: Combined solution plan view (not to scale)

5.6.2 Project planning and cost estimation combined solution

Refer to Sections 5.3.4, 5.4.4 and 5.5.2 for the planning of individual projects within the combined solution. The construction timing of the submerged breakwater could be placed earlier in the project as it now exceeds the reef construction time by four months.

Cost estimation figures are obtained from adding the individual project cost estimations and adding maintenance nourishments (6 reshaping, 1 sand volume addition).

5.7 Conclusion

The proposed designs and their performance have shown in section 4.1.6. In the previous sections the required time and cost for each alternative have been determined. A summary of the effectiveness of the solutions is shown in the table below. The zero-alternative, in which only a new western groyne is built, and regular nourishments are performed, is used as a reference for remaining erosion and a price for this option is indicated. For all other alternatives, the relative reduction of erosion (or if negative, accretion) of the Oasis beach, compared to this zero-alternative is given, as well as the respective total cost, rounded up to a thousand CUC.

Note that the remaining erosion of the artificial reef in case hurricane Irma is used as a normative 1-in-10-year storm is mostly caused by alongshore transport in deep water due to the large angle of incidence the waves have. Also note that due to the reference frame of the sedimentation measurements, the sedimentation shown for the artificial breakwater is likely to occur outside the sheltered area, on the toe of the breakwater. The price of the combined solution does not exactly equal the sum of the Artificial reef and Submerged breakwater alternatives, as the zero alternative is included in both solutions and some optimisations in price were made for the combined solution.

Table 5.16: Comparison of detailed designs based on erosion and price

Alternative	Remaining erosion Irma [%]	Remaining erosion Wilma [%]	Total Cost of Ownership [CUC]
Zero-alternative	100	100	$526,000. -
Artificial reef	12.0	2.8	$903,000. -
Submerged breakwater	4.8	-8.8	$1,896,000. -
Combined solution	2.3	1.6	$2,493,000. -

6. Conclusion and verification

6.1 Conclusion

If no measures are taken, no recreationally valuable beach will exist at the newly built Oasis resort. At the time of writing, erosion rates are only slowing down, because of the low erodibility of the remaining layer of coarse sediments and underlying bedrock.

Development of Oasis beach for 30 years to come is possible at a minimum expense of roughly $500,000. This zero-alternative however, is not considered durable as nourishment activities would exceed a frequency of 1.3 times per year on average in its lifetime, based on the 1 in 10-year tropical storm affecting Varadero. This will disturb recreational activity on the beachfront as nourishments will have to be performed between November and May, which coincides with the greatest number of tourist visits to the area. Another significant downside of this solution is the extraction of about 600,000 m^3 of sand in 30 years from the offshore cayos for the Oasis beach alone. This could have severe implications for the marine ecology of the offshore cayos. The financially attractive option of minimalistic intervention is thus not a choice that can be justified any further.

The durability of the sector also greatly relies on population and capital safety. Statistically, the lifetime of the project will be marked by the occurrence of three hurricane events. Flood risk was reduced by heightening the dune system. It was found that, for the 30-year project lifetime, the evacuation capacity of the road system suffices, but for a minimal evacuation time, evacuees must be divided over cars and buses in a 50/50 ratio, for which a shortage of cars currently exists in Varadero.

The best coastal protection scheme against tropical cyclones was found to be the 800-metre long, shore parallel submerged breakwater, combined with the so-called zero-alternative, which includes an initial nourishment and a groyne at the western boundary of the Oasis beach. Though a vast operation, this structure should be constructible at a tariff of $1,900,000. This includes: demolition of existing structures, groyne construction, initial nourishment and marina entrance extension.

An artificial reef is particularly effective in combatting the year-round erosion of Oasis beach in cross-shore sense. It creates the opportunities of adding new recreational dimensions to the beach as well as expanding coastal defence capacities over time. It can be realised at a total lifetime cost of $900,000, including the zero-alternative. This intervention will require regular monitoring and possible maintenance in the first five years of coral growth.

Combining a submerged breakwater (-5 m MSL) with the artificial reef (-3 m MSL) seems the best alternative to protect against all wave conditions, including hurricanes. The total cost of this intervention amounts to approximately $2,500,000, making it the most expensive solution, though the most effective.

In short, taking no action or constructing minimal interventions offer no durable development for Oasis beach. Spending $900,000 dollars on an artificial reef to gain a Varadero quality beach for 30 years to come will undoubtedly be a wise investment. As the artificial reef is both the most cost-effective solution and provides possibilities for recreation for the many tourists who will visit the Oasis hotel, construction of this measure is advised.

The project can be executed before May 2022 if initiation takes place in December 2019.

6.2 Verification and validation of definitive design

In Section 1.6 the demands to the final solution of "Durable Development of Oasis Beach" have been specified. In this section, the verification and validation of the final design will show the fulfilment of all demands.

6.2.1 Cross-reference of design and demands

The final design considers a detailed design for the Oasis beach sector and an analysis of the evacuation procedure of the Hicacos peninsula. In Table 6.1 all numbers of demands are listed, and it is indicated which of the proposed structures can be used to fulfil the demand. 'X' represents the solution contributes to the fulfilment of the demand, 'A' indicates that multiple solutions are alternatives to each other. The top demands are checked off if all underlying demands have been fulfilled (verification) without leaving performance gaps (validation). Blank spaces indicate that a demand is not fulfilled by this object. In the final column, a reference is given to the section of this report, where the background information used for the verification of the demand can be found.

In the next subsections, a short comparison between the alternatives is given and the demands are discussed separately. Specification is given to whether and how the demand has been fulfilled for the final design, which includes the beach nourishment, western groyne and artificial reef. As the existing Paso Malo groyne cannot be removed, but will influence the performance of the other objects, it is included in the table.

Table 6.1: Cross-reference of demand verification

Demand	Nourish-ment	Groyne	Artificial reef	Break-water	Existing Paso Malo groyne	Existing road infra-structure	Existing transport modes
B1.	X	X	A	A	X		
B2.	X	X	A	A	X		
S1.	**X**	**X**	**A**	**A**	**X**	**X**	**X**
S1.1	X	X	A	A	X		
S1.2	X	X	A	A	X		
S1.3						X	X
S1.4						X	X
S2.	**X**	**X**	**A**	**A**	**X**		
S2.1		X	A	A	X		
S2.2	X						
C1.	X	X		X	X		
C2.			X				
L1.	X	X	A	A	X	X	X
L2.	X	X	A	A	X	X	X
I1.	**X**	**X**	**A**	**A**	**X**		
I1.1	X	X	A	A			
I1.2	X						
I1.3	X	X	A	A	X		
I1.4	X	X	A	A	X		
I2.	**X**	**X**	**X**		**X**	**X**	**X**
I2.1	X	X	A	A	X	X	X
I2.2	X	X	X		X		
Bc1.	X	X	X	X	X		
Bc2.	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Bc2.1	X	X	X	X	X	X	X
Bc2.2	X	X	X	X	X	X	X
F1.	**X**	**X**	**X**	**X**	**X**		

6.2.2 Comparison of demand fulfilment

The artificial reef is chosen as the most viable alternative, mostly as it is a significantly more cost-effective method than the breakwater, or even a combination of the two. Therefore, the cost-effectiveness demand, specified in I2.2 is not fulfilled by the breakwater design. The table clearly indicates that for the most part, the breakwater and artificial reef are equal. The only difference, apart from the cost aspect, is the required specialist divers to install Reef Balls™, resulting in the need for external expertise, thus not directly fulfilling constructability demand C1.

6.2.3 Verification and validation of artificial reef performance

To be able to declare the definitive design successful, a short assessment of the demands is needed. For clarity, the following assets are included in the final solutions:

- Existing Paso Malo groyne, without alterations
- A groyne on the western boundary of the Oasis beach, newly constructed
- Reef Ball system at the 3-metre depth contour, newly placed, coral planted

The fulfilment of demands is verified by model outcomes in XBeach and Simio. As some parent specifications have been formulated quite generally, any outcomes of the model, which do not directly relate to the underlying child specifications but may influence the fulfilment of the general demand, are described in verification and validation, indicated by 'V&V'.

B1.

Specification: The solution must provide and protect a beach width of 40 metres along the entire Oasis beach section during the complete lifetime. Maintenance nourishment is allowed.

V&V: The initial nourishment profile has the required dimensions. Erosion is expected to occur, and maintenance nourishments will be needed to add lost sediment and to reshape the beach after hurricanes.

The total number of maintenance and reshaping nourishments, as shown in Table 4.4 is six, of which six will be used to reshape the beach and add lost sediment due to storms, and one will be used to add the lost sediment volume due to structural erosion. The beach will have the required dimensions during its lifetime, except directly after extreme storms, when it will need to be reshaped. The beach width can therefore be guaranteed during the entire lifetime, with minimal downtime for maintenance (approximately two weeks over thirty years, of which most will be outside of the high season).

B2.

Specification: Bedrock must be completely covered by a sandy layer from the dry beach through a water depth of three metres.

V&V: The design of the nourishment shape as defined in Section 5.3.2, shows the nourishment to run down to a depth between MSL-3.0 and MSL-4.0. The artificial reef lies at a depth of MSL-3.0 and stabilizes all sediment in landward direction. As the expected erosion is only 13,000 m^3 over a lifetime of 30 years, it is unlikely that any bedrock will be exposed in the swimming zone, taking maintenance nourishments into account. It is expected that natural avalanching due to sediment loss and sediment stirring due to wave dissipation will even out the sandy layer, resulting in an uninterrupted sandy seabed at the required depth. Monitoring will be required to find if local flow effects will affect the sand distribution, though from preliminary results, this is not expected to be the case.

Safety

Parent specification: **S1.** Storm safety: The solution must be storm-safe, as specified by the underlying demands.

V&V: This specification was verified by the fulfilment of the underlying demands. No model outcome resulted in any risks of flooding or additional safety risks due to flooding, as compared to the existing situation. Therefore, the Oasis beach section is considered storm-safe. Note that several of the child specifications indicate required maintenance after storm damage. To maintain storm safety of the Oasis sector, these maintenance indications must be followed.

Child specification: **S1.1.** The Oasis section must not flood in case of a normative, 1-in-ten-year storm.

V&V: The Oasis beach section will be significant after this storm, as indicated in the model results in Section 4.1.4. The dunes, however, suffer little erosion, as the protective artificial reef reduces wave height to a point where the dissipation takes place mainly before the dunes. The Oasis section will thus not fail as a flood protection system due to hurricane conditions. Note that the adjacent beach section and water levels in the Paso Malo during hurricane conditions are likely to cause some overtopping of the harbour channel at the least. XBeach models have not indicated structural inundations, but the behaviour of waves in the Paso Malo channel may be investigated further.

S1.2.

Child specification: Hard structures must be stable during a normative, 1-in-ten-year storm.

V&V: All hard structures, of which detailed designs can be found in Section 5, have been designed based on design conditions, which either follow from storm wave parameters directly, or from the physical maxima to the possible wave heights on the respective locations of the structures (due to depth induced breaking or sheltering by other structures). The damage level used is 2, which means small damages (such as movement of the outer rock layer) are allowed, but the structure will not fail, thus fulfilling the demand.

Note that to prevent failure due to the accumulation of storm damage, visual inspection (above and below water) is required, and any damages are to be repaired to prevent loss of stability of the structure over time.

S1.3.

Child specification: In case of a hurricane, sufficient transport modes must be facilitated for the evacuation of the increasing number of tourists on the Hicacos peninsula.

V&V: The Simio modelling in section 4.2 indicated that the required time to evacuate, varies for a changing ratio of cars and buses used in the evacuation. The optimal ratio of evacuation is found when half the evacuees are transported in buses and the other half in cars, which will result in an evacuation time of 22.5 hours for the largest projected growth in tourism.

S1.4.

Child specification: Evacuation of the peninsula must be finished before the waves overtop onto the main road.

V&V: The time available before this normative situation is reached, varies with the moment in which the decision is made to evacuate. As the main road of the Hicacos peninsula lies on the east, near the water line, the available time for evacuation during hurricane Irma is chosen, as this hurricane travelled from the East, resulting in wave overtopping on the Autopista Sur. A target time for evacuation of 24 hours was determined from this hurricane scenario. All simulations indicated that it is possible to evacuate within this timeframe, if the correct balance between transport modes (cars and buses) is used for evacuation.

S2.

Parent specification: Swim safety: The solution must be safe for recreational swimmers, as specified by the underlying demands.

V&V: This specification was verified by the fulfilment of the underlying demands. No model outcome resulted in any risks in the swimming area during normal conditions, with regard to unpredictable or high return flows, wave height variations or bed level variations. Therefore, the Oasis beach section is considered swim-safe. Note that the swim safety for cold front or even hurricane conditions is not assessed, as it is deemed common sense not to use the swimming area in these conditions.

S2.1

Child specification: Flow speeds in the swimming area must be smaller than 0.20 m/s in normal conditions.

V&V: The model of Oasis beach in normal conditions indicates small alongshore flows to the west at a depth of one to two metres. These flows pose no direct hazard to tourists and only exceed the required value at a depth of less than 0.5 metres. The flows are directed alongshore, and thus do not result in swimmers being moved offshore. Therefore, the demand is deemed sufficiently fulfilled.

S2.2

Child specification: The depth profile in the swimming area must be sloping predictably and gradually.

V&V: The nourishment profile indicated in section 5.2 has a constant slope of 1:20 through a depth of at least 3.0 metres, well beyond the point where swimmers may stand in the water. The models for normal and cold front conditions indicated no local points of significantly different sedimentation or erosion, thus preserving the slope of the swimming area in all regular conditions. As it has been indicated before (in the verification and validation of demand B1.1), maintenance nourishments are required to reshape and add to the beach after hurricane conditions. Therefore, the profile after a hurricane was not considered relevant to this demand and has not been analysed.

Constructability

C1.

Specification: A solution which is constructible for Cuban contractors is preferred.

V&V: The construction of the final design requires some input from parties outside of Cuba. The western groyne and beach nourishment are relatively traditional solutions, for which Cuban engineers and contractors have more than sufficient expertise to construct, independent of any external party. The artificial reef requires input from specialists outside Cuba on two points, which will be discussed in the verification of C2. Though not all of the structures can be constructed using Cuban specialists, for two out of three measures, the specification is fulfilled.

C2.

Specification: For non-traditional solutions, the required external expertise must be indicated in the work method.

V&V: The production of the Reef Balls™ requires specific moulds for casting concrete, which will need to be imported. The installing of the concrete elements requires trained divers. As the Reef Balls™ have been used in various other locations throughout the Caribbean, the required expertise is easily available. Therefore, the demand is deemed to be fulfilled.

Lifetime and maintenance

L1.

Specification: The solutions on Oasis beach will have a lifetime of 30 years.

V&V: Both the design of the Oasis beach section and the evacuation analysis are fully based on the upcoming thirty years of tourism. The design of the artificial reef solution is based on the erosion expected in a thirty-year lifetime caused by normal, cold front and hurricane conditions, and the various concept designs have been evaluated based on the erosion expected to occur in this period. The evacuation analysis is based on various projections of the growth of tourist numbers in Varadero between 2018 and 20148 and thus provides advice for the same timeframe.

L2.

Specification: Nourishments within lifetime are allowed but must be included in the total cost of ownership (TCO).

V&V: All definitive designs include a detailed cost plan, see Section 5. An estimate of costs of maintenance nourishments and nourishments required to reshape after extreme conditions is given, based on the PRECONS II cost sheets, published by the Cuban government. Therefore, all nourishments are accounted for. The number of required nourishments per alternative can be found in section 4.1.6.

Interfaces

I1. Physical interfaces

I1.1

Specification: The old Oasis hotel building may or may not be demolished and should thus be considered a physical interface to the project area.

V&V: The old Oasis building has not been specifically modelled in any XBeach design, as the concept designs of the solutions already indicated a significant reduction of the erosion in the dunes. After the dune vegetation was added in the definitive design models, the dune erosion did not affect the location of the former Oasis hotel no longer. Therefore, the models were accurate, without the specific inclusion of the presence of the former hotel. The demand has therefore not been fulfilled directly but has become obsolete due to the development of the design process.

I1.2 The Paso Malo harbour entrance must not be closed.

V&V: The western groyne of the Paso Malo has been selected as the eastern boundary for the development of Oasis beach, to prevent any negative influence on the Paso Malo. For the proposed final solution, the artificial reef, no measures are taken near the Paso Malo entrance, as the nourishment will not reach to the end of the Paso Malo and the artificial reef will be placed approximately at half the offshore length of the groyne. The new western groyne is approximately the same length as the Paso Malo groyne, thus not shielding the channel in normal, cold front or hurricane conditions.

The magnitude of offshore sediment transport in normal or cold front conditions, resulting from the XBeach models (Section 4.1.6) is too small to cause siltation of the harbour entrance. During hurricane conditions, the Paso Malo entrance may experience siltation due to offshore sediment transport. As it is common practice to perform maintenance nourishments after such an event, this effect is not considered a problem, which means the final solution fulfils this demand.

I1.3

Specification: Expansion of the Autopista Sur is undesirable, due to the minimal physical space available.

V&V: The road capacity of the Autopista Sur was analysed in the Simio simulation, see Section 4.2. The capacity of the road was not found to be the most important factor in the evacuation of the peninsula. The distribution of evacuees over different modes of transport and the minimal car ownership in Cuba are currently the most important limits to the evacuation capacity. Once car ownership rises in Cuba, the road capacity may become a factor of interest. For now, the expansion of the Autopista Sur is not advised and this demand is not of importance.

I1.4

Specification: The proposed solution must not negatively affect the nearby beaches.

V&V: The solution proposed includes one measure, which may affect the shoreline of the adjacent coastal sections: the western groyne. In normal conditions, alongshore sediment transport runs from east to west. In these conditions, the western groyne blocks sediment outflow from Oasis beach to the adjacent coast. The coast west of Oasis currently consists of bedrock, mostly covered by a layer of loose rock. The presence of sediment is minimal. There are no current plans to develop this area in similar fashion to Oasis beach.

Although the construction of the western groyne will complicate the construction of a beach west of Oasis if this becomes desirable in the future, a similar solution as designed for Oasis, which again incorporates a new groyne on the western end of a new beach section, would likely result in a stable beach again. Therefore, the necessity of the prevention of alongshore sediment transport is deemed more important than the complication of hypothetical future development and the negative effects of the Oasis beach design are deemed to be minimised, thus fulfilling the demand as good as possible, without compromising the quality of the Oasis beach.

I2. Logical interfaces

I2.1

Specification: The solutions must be suitable for the expected tourist growth during the lifetime of the Oasis beach.

V&V: The design of Oasis beach suits the capacity demands of the client. The storm safety for the growing tourist demand has already been discussed in the verification and validation of specification S1.3. The growth of the hotel area beyond Oasis beach has not been determined yet and can thus not be designed for. The demand therefore is fulfilled as far as current information allows. Note that the expansion of the beach to the west, as discussed in the validation of demand I1.4, is slightly more complex due to the new groyne, but is still possible in a similar manner as the proposed development of Oasis beach.

I2.2

Specification: The total cost of ownership (TCO) of the beach development may only be increased if this results in direct benefit to tourists in the form.

V&V: The TCO of all solutions is specified in Section 5. The main driver of the advice to construct an artificial reef is the minimal reduction of nourishments (and thus beach downtime) by a breakwater, compared to the increase of the TCO. Apart from this, it is expected that in the long-term (after approximately five years), the reef has developed sufficiently to be stable without maintenance and suitable for tourist activities, such as diving and snorkelling. The additional tourist attraction combined with the reduced price, compared to the breakwater, means the artificial reef is the most suitable solution to fit this demand.

Boundary conditions

Bc1.

Specifications: The closest sand mining site lies near Cayo Mono, approximately 25 km from Oasis Beach.

V&V: The distance to the sand mining site is the basis of the fuel consumption and running time of both initial and maintenance dredging. The boundary condition has thus been implicitly used in the project, as an influence on the total costs as indicated in Section 5.

Bc2.

Parent specification: The following developments in design conditions over the Oasis beach lifetime must be considered.

V&V: The boundary conditions have been considered in the determination of the design conditions. Please see the specific conditions for separate discussion of the implementation in design.

Bc2.1

Child specification: Sea level rise for the next 30 years (needs to be considered in the design conditions).

V&V: The projections of mean sea level change in front of the Varadero coast, as published by the IPCC (IPCC, 2017), are between zero and minus two mm per year change. The expected reduction of sea water level thus results in an expected reduction of 6.0 cm of the sea water level. The only demand which could be affected is demand B2 (no exposed bedrock is allowed in the swimming area to a depth of 3.0 metres), which would result in a six-centimetre shortage of sediment at the deep end of the swimming area. This difference is so small, that it can be easily solved with a small increase of volume of the maintenance nourishments. Therefore, the influence of sea level rise is deemed minimal and the demand is fulfilled.

Bc2.2

Specification: Trends in normal and storm conditions (need to be considered in the design conditions).

V&V: The determination of design conditions in Section 2.5 considers a characteristic value of the normal conditions as the design value. As the data used does not indicate trends, this value is considered an accurate representation of the normal wave conditions which are to be expected for the next thirty years.

For hurricane conditions, this was not the case. As minimal data is available about the representative design conditions for a hurricane, a statistical extrapolation resulted in a normative wave height, based on which representative hurricanes were chosen as design conditions. The path of the hurricane showed to be of such great influence on the erosion of the Oasis beach, that the maximum erosion between the two storms was used as a best guess of the erosion to be expected during the storms during the lifetime of the Oasis beach. The demand was therefore fulfilled as good as possible, based on available data, but the limitations of probabilistic design must be noted. The damage done by one extreme storm with a path similar to Irma, but now passing just slightly north of the Cuban coast may be so large, that an additional full restoration of the nourishment may be necessary.

Product format

F1.

Specification: All proposed final designs must include a work method and cost estimate.

V&V: All viable concepts have been developed to a definitive design, with a higher level of detail, based on which exact workplans can be written. The costs and an estimation of the work schedule have been given, based on which the preferred final design has been selected. The demand has therefore been fulfilled for four design alternatives.

6.2.4 Verification of design

The final design fulfils all demands; however, some additional effort may be needed in maintenance to make sure this remains the case throughout the projected lifetime of thirty years. The most important monitoring during the lifetime of the Oasis beach is after hurricane conditions. Any damages to structures need to be repaired and it is to be expected that maintenance nourishment is required. Another point of interest in this final design is that it is not impossible, but slightly more complicated to extend this beach to the west, as the new western groyne will cut off sediment supply to this beach in the same way the Paso Malo groyne does for the Oasis beach now. The remainder of the demands pose no further problems and the definitive design of the Oasis beach successfully fulfils its specifications.

7. Recommendations

This project was carried out, using current sources of data on the Oasis beach sector. Contemporary literature was consulted alongside more established sources. A variety of sources were used such as documentaries, press releases, meta-analyses, guides, MSc theses and academic journals from the international community as well as local (Cuban) productions. There are still some facets that remain unaddressed in this report despite this wealth of information, of which the most important are listed below.

The authors recommend a preliminary research of Cuban investment policy and asset management before engaging into another engineering study. As of today, 40 years of erosion related research have produced little to no outcome for various coastal sections in Varadero.

Secondly, not every civil engineering project can be resolved with civil engineers alone. Especially the introduction of biotechnology into the solution space posed challenges that lie outside the curriculum of civil engineers. 'Durable Development of Oasis beach' would benefit from the inclusion of climatologists, ecologists, bio-engineers etc.

Information regarding traffic flows is not actively gathered in Cuba. The data for this project was accessed with difficulty, and often disregarded due to a lack of quality and reliability. A recommendation is made to the relevant authorities to monitor traffic flows on the Hicacos peninsula. The simulation of evacuation may be expanded to a more realistic scenario by indicating multiple destinations in the evacuation model.

The level of detail of the model may also be increased by a more accurate approximation of the spreading of tourists over the peninsula. For this research, the model was simplified to five main hotel areas, from which tourists were evacuated. Adding another sublevel by dividing these areas into separate nodes for each hotel may result in a more realistic simulation of the evacuation transport flow.

Modelling strategies regarding coral reefs are still in an early stage of development. Future research should focus more on accurate representation of reef crests, reef flats and different artificial reef substrates. Decoupling the reef from the bathymetry would be a first step. This way, characteristics such as rugosity, porosity and growth can be applied. The latter would ideally be incorporated in Delft3D and/or XBeach.

Furthermore, the effects of hurricanes on the uplift of reef elements that are not fixed to the seafloor are unsure. Fixation of only the outer units was based on literature and did not involve modelling or manual calculations. It may be wise to anchor all elements to the sea floor. This will require a significant additional investment, as the fiberglass anchor elements are the most expensive component of the reef balls, but it may prevent large damages during hurricanes.

More accurate modelling of the local wave climate should be possible. The current datasets at-hand are relatively small and allow for misinterpretations of the year-round climate. Also, the crude modelling of the dune vegetation in the definitive design models may be detailed to represent the current situation more accurately.

Finally, the use of Delf3D software should be able to provide a more in-depth relation between sediment transport processes on the larger timescale. Such a long-term model simulation is advised before design development and construction are initiated. This model should include aeolian (wind) transport as well, which was not accounted for in the Xbeach models used in this project.

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Appendices

A. On-site investigation

Introduction

To inspect the current state of the Oasis beach sector and the possibilities for future use, a day trip to the project location and the surrounding area on the Hicacos peninsula was organised by Professor Córdova and Gamma Engineering. This appendix describes the activities of the day and the information gathered on site.

Participants

The following participants attended the visit to the project site:

Prof. Luis Cordova – Professor in Hydraulic Engineering at CUJAE University of Havana, project initiatior

TU Delft project team:

Jouke Binsma

Joyce Helmer

Casper Onnink

Bram Verbeek

Lic. Pavel Morales Díaz – Coastal engineer at Gamma engineering

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Schedule:

8:15 – 10:45	Transport Havana – Oasis beach
10:45 – 13:30	Site inspection Oasis beach
13:30 – 14:30	Lunch
14:30 – 16:00	Hicacos Peninsula visit
16:15 – 19:00	Transport Hicacos – Havana

The visit to two parts of the Varadero coast proved to be very valuable in establishing a good understanding of the coastal and urban layout of the area. Significant observations are described below.

Figure A1 shows the layout of the western side of the beach, where a small half-buried cold war bunker can be found. The grainsizes here are the coarsest of the entire beach section with even some pebble deposits.

Figure A1. Western boundary Oasis beach

Figure A2 shows the all-round exposure of bedrock on the waterline.

Figure A2. Impression of the overall beach layout at Oasis beach

Cusps start to appear when moving eastwards along the beach, Figure A3 shows the maximum cusp height found at the central part of the beach which is about 1.0 m. Also, the slope close to the waterline is rather steep.

Figure A3 – Tallest cusps present at the vegetation border

Fig A4 is a good depiction of the diffraction patterns around the Paso Malo groyne. These patterns cause the concave shape of the coastline west of the marina.

Figure A4 – Diffraction pattern caused by Paso Malo groyne

A large zone of accretion is found east of the marina entrance (Figure A5), just outside of the project beach area. Sometimes, this zone is used to borrow sand for small profile reshaping works, indicating the extent of sediment catchment by the double groyne.

Figure A5 – Paso Malo waterway (front), accretion zone (back)

A typical wide Varadero beach is depicted in Figure A6. Strong longshore currents were observed here.

Figure A6 – The beach layout at a northern section of Peninsula de Hicacos

B. List of Demands

This overview of the demands was made during the development of the program of demands. A completed version can be found in section 6.2.4 Verification of design, in the verification of the demands.

Demand	Object A	Object B	Object C	Object D
B1.				
B2.				
S1.				
S1.1				
S1.2				
S1.3				
S1.4				
S2.				
S2.1				
S2.2				
C1.				
C2.				
L1.				
L2.				
I1.				
I1.1				
I1.2				
I1.3				
I1.4				
I2.				
I2.1				
I2.2				
Bc1.				
Bc2.				
Bc2.1				
Bc2.2				
F1.				

C. Stakeholder problem perception

In table C.1 an overview of the problem formulation is given for each stakeholder that is concerned with the Durable development of the Oasis Beach sector. This overview is used to compare the interests and desired situations between all stakeholders, to identify similarities and differences between actors (Enserink et Al., 2010) .

Table C.1. The problem perception of the stakeholders

Ministries	Interests	Desired situation	Existing situation and gap	Causes of gap	Possible solutions
Ministry of Tourism MINTUR	To expand and improve the tourist sector in Cuba, focusing strongly on beach tourism.	Sufficient capacity of beach area and hotel rooms, mostly for international tourism in the 4-5-star range.	Due to increasing tourist demand, over 100,000 new 4-5-star hotel rooms, of which most will be on the beachfront, need to be developed, and the beach space needs to grow with this demand before 2030.	Lack of capacity to facilitate sufficient tourists.	Construction of hotel and nourishments and protection of sandy beach area.
Ministry of Construction MoC	Constructing a variety of large works in Cuba.	A structure has been built which suits the needs of the touristic sector and provides work to the construction sector.	Scope for construction has not been defined yet.	Technical difficulty of project, low necessity of project until now.	Set scope and design solution to construct.
Ministry of Armed Forces (Force Arma Revolutionnaire) MINFAR	As the owner of GAESA holdings and Gaviota hotels, the Armed forces want to profit as much as possible from their hotels along the Hicacos peninsula.	GAESA hotels returns a rising profit from the Hicacos peninsula.	The hotels are divided under three big holdings Cubanacán, Gran Caribe and Gaviota.	There is heavy competition between the three holding companies.	GAESA will own most of the hotels in the Oasis sector.

Ministries	Interests	Desired situation	Existing situation and gap	Causes of gap	Possible solutions
Ministry of Science, Technology and Environment CITMA	To protect the environment of Cuba and thus of the Hicacos peninsula against negative human influences.	The Oasis sector is a stable nourished beach, with a minimal amount of man-made structures and minimal change in the environment.	A significant shortage of sediment in the Oasis sector poses a threat to the local ecosystem.	The Oasis sector shows strong erosion, which is expected to continue until bare rock remains.	A beach nourishment combined with minimal hard structure solutions to preserve the natural ecosystem.
Ministry of Labour and Social Security MTSS	To create more jobs in the tourist sector. To provide safe working conditions for workers.	The expanding tourism in Varadero provides more job opportunities in good conditions.	Touristic opportunities are in development. Jobs are expected to become available, but the supply is chasing the demand.	The developments in Varadero have not kept up with the growing touristic demands.	The development of new hotels and other facilities needs continue to provide more jobs.
Ministry of Transportation MINTRANS	To ensure sufficient capacity to transport people and goods to the Hicacos peninsula.	The Hicacos peninsula is accessible, both in normal and in storm conditions.	Increasing load on the transportation system.	The expansion of the touristic use of the Hicacos peninsula.	Additional infrastructure and/or public transport.
Ministry of Banco Financiero Nacional	To make sure the project has an optimal return on investment.	To have a profitable Oasis Hotel after expenses on the beach and hotel.	The investment in the hotel has been made, the investment in the beach will be made later. Returns have not yet been realised.	Complexity of the beach development, time required to complete hotel.	Either minimizing expenses on the beach or realizing additional income from the beach.

Institutes / companies working for the government	Interests	Desired situation	Existing situation and gap	Causes of gap	Possible solutions
Institute for Physical Planning	To find suitable operators for the Oasis beach sector and to approve a permit of long-term operation.	The best hotel operator is given a permit and the hotel is profitable.	There is neither a completed hotel, nor a beach attractive for tourism.	Slow decision making, Complexity of the beach development, time required to complete hotel.	Completion of hotel and beach to be able to formally permit the hotel.
Hotel Operators	To operate as many profitable hotels as possible under a management agreement with the ministry of Tourism.	To have a profitable hotel.	There is neither a completed hotel, nor a beach attractive for tourism.	Slow decision making, Complexity of the beach development, time required to complete hotel.	Completion of hotel and beach to acquire the permit to operate the hotel.
Gamma engineering	To research and provide technical expertise to the government of Cuba.	To find the best solution to expand and preserve the Oasis beach sector.	Limited experience and resources in the specific field, especially in relation to coastal modelling of storm situations.	Local specialist expertise and resources unavailable.	To design and implement a solution based on a rule of thumb.
Real Estate holding Companies	To maintain the hotel buildings throughout Cuba.	To perform maintenance on the Oasis hotel.	Oasis hotel is under construction, the design of the beach and influence on maintenance has not yet been determined.	Complexity of the beach development, time required to complete hotel.	Consideration of hotel maintenance in beach nourishment and design, to prevent additional cost.
Centre of Environmental Services of Matanzas	To protect the environment of Matanzas and thus of the Hicacos peninsula against negative human influences.	The Oasis sector is a nourished beach, with a minimal amount of man-made structures and minimal change in the environment.	A significant shortage of sediment in the Oasis sector poses a threat to the local ecosystem.	The Oasis sector shows strong erosion, which is expected to continue until bare rock remains.	A beach nourishment combined with minimal hard structure solutions to preserve the natural ecosystem.

Institutes / companies working for the government	Interests	Desired situation	Existing situation and gap	Causes of gap	Possible solutions
Institute of Oceanography	To research all coastal processes in Cuba and to determine if engineering measures are required.	To find the most suitable engineering intervention for Oasis beach.	Lack of involvement in the matter.	CUJAE is currently in the lead of developing options for the Oasis sector.	The institute works in cooperation with Gamma to find the best solution for Oasis beach.
GAESA	To turn a profit on the companies they operate.	As the owner of Gaviota hotels, GAESA wants to profit as much as possible from their hotels along the Hicacos peninsula.	The hotels are divided under three big holdings Cubanacán, Gran Caribe and Gaviota.	There is heavy competition between the three holding companies.	GAESA will own most of the hotels in the Oasis sector.
Gaviota	Managing the most profitable hotels, tours and transportation through their assets.	To own profitable hotels in the Oasis sector.	The hotels are divided under the three holding companies Cubanacán, Gran Caribe and Gaviota.	There is heavy competition between the three holding companies.	Gaviota will own most of the hotels in the Oasis sector.
Cuban Construction firms	To get the most projects assigned by the ministry of Construction.	To build the Oasis beach and hotels in that specific sector.	There is yet no assignment to be given.	Design of the expanding of the Oasis beach is not complete.	The design is constructible for local companies and awarded to a Cuban contractor.

Other stakeholders	Interests	Desired situation	Existing situation and gap	Causes of gap	Possible solutions
CUJAE	To research and educate on various fields of study.	To show that highly educated engineers can also contribute on operational level.	The provided projects in the previous years were to general to implement.	Priorities on academic level instead of practical applicability.	A project which is realistic, considering budget and equipment available in Cuba.
Municipality of Varadero	To improve living standards in Varadero.	To gain profit from the increasing number of tourists.	Failure to capitalize on growth of touristic interest in Varadero.	Shortage of hotel space and beach area available.	Increase of hotel and beach space while maintaining safety.
External contractors	Acquiring a contract to apply their services to make money.	To get assigned to do the nourishment work for the Oasis beach and/or the hydraulic hard structures	External (non-Cuban) contractors are at a disadvantage.	Design of the expanding of the Oasis beach is not complete.	The get assigned to the project, when scope is too complex for Cuban contractors.
External experts	To give their opinion and propose new and innovative work methods.	To give the best possible solution according to their research for the Oasis sector.	The experts find an interesting engineering problem to solve, considering coastal morphology and land use.	Lack of local knowledge and experience in the field of Hydraulic engineering.	Offer the best solution for the Oasis sector.
Tourists	To enjoy a luxury vacation in Varadero.	A 5-star Oasis hotel with a beautiful white beach.	The hotel is not built yet, the beach is not up to par.	The Oasis sector shows strong erosion.	Finish the hotel and improve the Oasis beach.
Car rental companies	To make a profit by renting out cars.	Touristic growth results in a strong increase in car rentals.	Difficulty to grow the business.	A shortage of cars on Cuba.	Import of vehicles to Cuba.
Transport (Bus, taxi) companies	To make a profit by selling bus tickets.	Touristic growth results in a strong increase in bus tickets sale.	Difficulty to grow the business.	A shortage of (good quality) buses on Cuba.	Import of vehicles to Cuba.
Province of Matanzas	To improve living standards in Matanzas.	The tourism around Varadero thrives.	Capacity in hotels and beach space is in short supply.	The Oasis section shows strong erosion.	Finish the hotel and improve the beach.

D. Network Analysis

In this appendix the more detailed images are given for the expected critical infrastructure areas in time of evacuation.

Figure D.1 shows the most funeral area of the road infrastructure on the peninsula. Namely, the bridge between the peninsula and the mainland of Cuba. As can be seen is this bridge the only way to mainland, so everyone will need to cross this bridge during evacuation. This could become a bottleneck depending on the capacity of the road and the number of vehicles. Furthermore, just after this bridge the road is split in the Via Blanca and the Avenida Tra, which leads to the town Santa Marta. The road to Santa Marta narrows from a two-lane road to a single-lane road, this could also become a bottleneck.

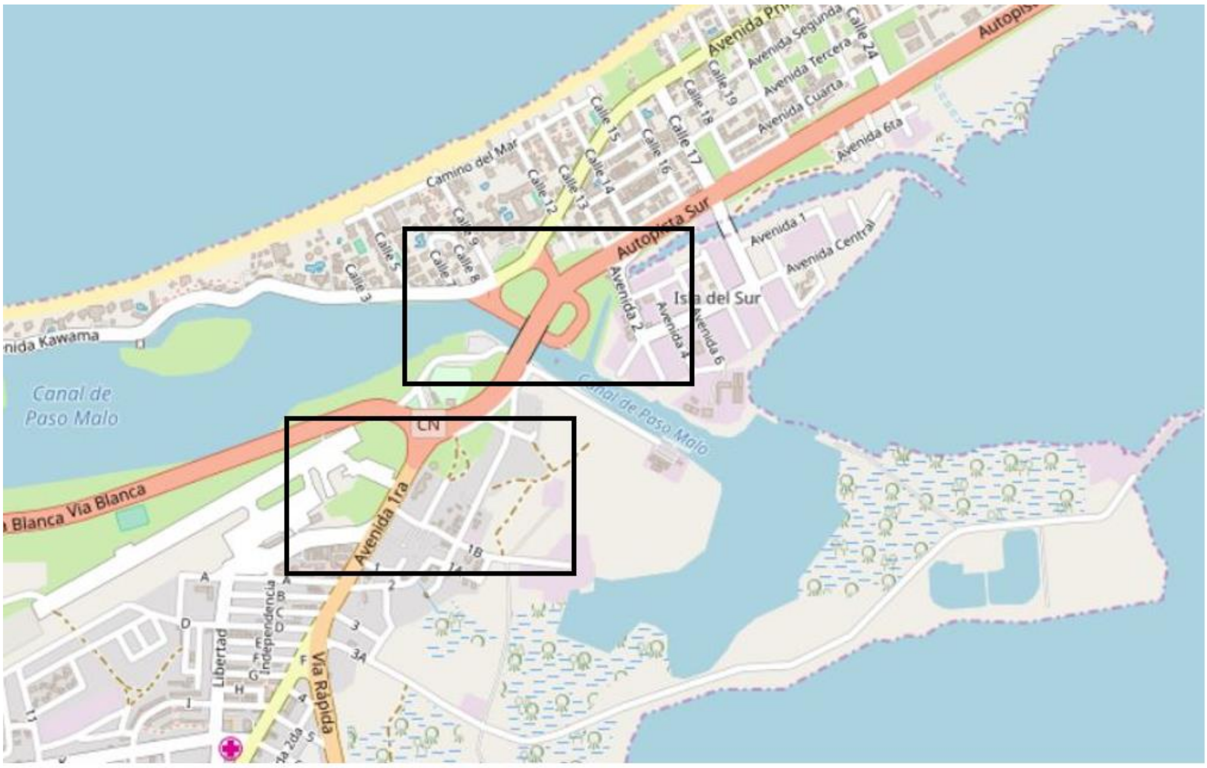


Figure D.1: Critical areas road infrastructure

Another area what could become a bottleneck is the area where the Avenida Primera comes together with Autopista Sur (figure D.2). The vehicles of the latter part of the peninsula and the vehicles from the north side come together and all need to drive in the same direction over the Autopista Sur.

Figure D.2: Critical area road infrastructure

E. Hurricanes

Table E1. Shows the five hurricane categories based on windspeed and the types of damage these categories can cause.

Table E.1 Hurricane categories

Hurricane Category	One minute sustained winds	Types of damage due to hurricane winds
Category 1	119-153 km/h	Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutter. Large branches of trees will snap, and shallowly rooted trees may be toppled. Extensive damages to power lines and poles likely will result in power outages that could last a few to several day
Category 2	154-177 km/h	Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks
Category 3 (major)	178-208 km/h	Well-built framed homes may incur major damage or removal of rood decking an gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
Category 4 (major)	209-251 km/h	Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted, and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
Category 5 (major)	≥ 252 km/h	A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months

Time-varying wave characteristics on the Oasis beach offshore boundary during hurricane Wilma.

Zs (surge/tidal waterlevel)	Hs (significant wave heigth [m])	Tp (peak period [s])	Mainang (wave angle of incidence) [degrees]	Gammajsp (jonswap peak factor) [-]	Dispersion angle [degrees]	Duration [s]	Dtbc+ (time step model) [s]
-0.01855018	0.934524232	20.94816385	83.49464621	3.3	10	3600	1
0.09911907	1.115724199	21.23815841	61.78993698	3.3	10	3600	1
0.21185703	1.372497868	21.35016492	36.3604728	3.3	10	3600	1
0.29729194	1.743056445	21.35190505	14.74728769	3.3	10	3600	1
0.33636248	2.236291236	21.27410367	1.5057961	3.3	10	3600	1
0.3200106	2.821817698	21.12105547	-5.8171816	3.3	10	3600	1
0.2533574	3.471403736	20.89002215	-10.0848207	3.3	10	3600	1
0.15433141	4.133771553	19.97542178	-12.81648977	3.3	10	3600	1
0.04708119	4.802426149	19.45068919	-14.7127097	3.3	10	3600	1
-0.04618106	5.476214692	19.22027958	-16.5138266	3.3	10	3600	1
-0.11071902	6.228101532	18.99931768	-18.8087179	3.3	10	3600	1
-0.14053059	7.013635274	15.24922075	-21.3468242	3.3	10	3600	1
-0.13687926	7.437482469	15.11469672	-23.8261231	3.3	10	3600	1
-0.10676186	7.330791745	14.99301075	-25.88052573	3.3	10	3600	1
-0.06231116	6.898829417	14.81589722	-27.21193647	3.3	10	3600	1
-0.01969435	6.299508214	14.57627796	-28.29957273	3.3	10	3600	1
0.0044661	5.655213956	14.19646063	-29.47234297	3.3	10	3600	1
-0.00098932	5.037006346	13.76186553	-30.81177977	3.3	10	3600	1
-0.003644854	4.477908424	13.51688472	-32.20841673	3.3	10	3600	1
-0.09047365	3.980665818	13.28972395	-33.49872027	3.3	10	3600	1
-0.14423804	3.542388099	12.96988447	-34.53525997	3.3	10	3600	1
-0.17903315	3.1576913	12.52976887	-35.2898173	3.3	10	3600	1
-0.18256833	2.821899555	12.26573523	-35.79927773	3.3	10	3600	1
-0.15122578	2.531776492	12.03058839	-36.10951943	3.3	10	3600	1
-0.08874347	2.28321074	11.73098684	-36.27390747	3.3	10	3600	1
-0.00400618	2.071557111	11.32396468	-36.3514831	3.3	10	3600	1
0.09004812	1.891342867	11.06478589	-36.38796183	3.3	10	3600	1
0.17693721	1.737037966	10.83089949	-36.42156167	3.3	10	3600	1
0.23873527	1.603639632	10.52264398	-36.47389927	3.3	10	3600	1
0.26088124	1.486856292	10.22565263	-36.5628886	3.3	10	3600	1
0.23794063	1.38285338	10.01138299	-36.7056701	3.3	10	3600	1
0.17667411	1.288887532	9.811438817	-36.90896803	3.3	10	3600	1
0.09388517	1.203057718	9.554198523	-37.18179523	3.3	10	3600	1
0.00995219	1.124516718	9.307930252	-37.54390663	3.3	10	3600	1
-0.0581659	1.052708301	9.11582051	-38.01135457	3.3	10	3600	1
-0.10075556	0.987680806	8.927138908	-38.6158467	3.3	10	3600	1
-0.1151658	0.929212306	8.690622593	-39.38677157	3.3	10	3600	1
-0.103757	0.876969332	8.484833028	-40.3449625	3.3	10	3600	1
-0.07264097	0.830519631	8.328567135	-41.50123287	3.3	10	3600	1
-0.03175653	0.789296761	8.181742935	-42.85777987	3.3	10	3600	1
0.00559419	0.752564644	8.014654427	-44.40775747	3.3	10	3600	1
0.02579427	0.719715968	7.767757685	-46.13976227	3.3	10	3600	1
0.02019824	0.690067188	7.593306017	-48.05750723	3.3	10	3600	1

Zs (surge/tidal waterlevel)	Hs (significant wave heigth [m])	Tp (peak period [s])	Mainang (wave angle of incidence) [degrees]	Gammajsp (jonswap peak factor) [-]	Dispersion angle [degrees]	Duration [s]	Dtbc+ (time step model) [s]
-0.01038896	0.663024064	7.449848764	-50.1536274	3.3	10	3600	1
-0.05538872	0.638351615	7.309426262	-52.41991357	3.3	10	3600	1
-0.09897552	0.615645623	7.132916247	-54.82544137	3.3	10	3600	1
-0.12971316	0.594933943	7.000287489	-57.36912217	3.3	10	3600	1
-0.16029267	0.57627012	10.89785569	-60.07138247	3.3	10	3600	1
-0.10828614	0.559449033	10.85889015	-62.7990334	3.3	10	3600	1
-0.06411311	0.544439491	10.81671771	-65.4005654	3.3	10	3600	1

Time-varying wave characteristics on the Oasis beach offshore boundary during hurricane Irma. Model runs start from the time point indicated by a bold line.

Zs (surge/tidal waterlevel)	Hs (significant wave heigth [m])	Tp (peak period [s])	Mainang (wave angle of incidence) [degrees]	Gammajsp (jonswap peak factor) [-]	Dispersion angle [degrees]	Duration [s]	Dtbc+ (time step model) [s]
0.240892405	1E-06	1.00E-06	1E-06	3.3	10.0	3600.0	1
0.245226359	1E-06	1.00E-06	1E-06	3.3	10.0	3600.0	1
0.248559717	1E-06	1.00E-06	1E-06	3.3	10.0	3600.0	1
0.242501056	1E-06	1.00E-06	1E-06	3.3	10.0	3600.0	1
0.225368372	1E-06	5.970268883	1E-06	3.3	10.0	3600.0	1
0.189879479	1E-06	12.85135621	263.4487311	3.3	10.0	3600.0	1
0.146548256	1E-06	19.95808394	246.5416521	3.3	10.0	3600.0	1
0.125044663	1E-06	31.86337096	253.4447129	3.3	10.0	3600.0	1
0.138833642	1E-06	31.86337096	252.673259	3.3	10.0	3600.0	1
0.171256391	1E-06	31.86337096	252.5854905	3.3	10.0	3600.0	1
0.191542066	1E-06	31.86337096	252.6057389	3.3	10.0	3600.0	1
0.184037168	2.67396E-06	31.86337096	252.6819871	3.3	10.0	3600.0	1
0.154428616	6.67424E-06	31.86337096	252.6461187	3.3	10.0	3600.0	1
0.119534299	1.4755E-05	31.86337096	252.7988083	3.3	10.0	3600.0	1
0.097602172	2.96353E-05	31.86337096	253.2059077	3.3	10.0	3600.0	1
0.097570952	5.31533E-05	31.86337096	253.6023718	3.3	10.0	3600.0	1
0.114558973	8.90126E-05	31.86337096	254.1493231	3.3	10.0	3600.0	1
0.138254896	0.000139543	31.86337096	254.5431626	3.3	10.0	3600.0	1
0.168094243	0.000204094	31.86337096	254.6827398	3.3	10.0	3600.0	1
0.200338153	0.000286598	31.86337096	254.6970678	3.3	10.0	3600.0	1
0.242578111	0.000383742	31.86337096	254.5788427	3.3	10.0	3600.0	1
0.293246044	0.000493516	31.86337096	254.3554184	3.3	10.0	3600.0	1
0.348953967	0.000613565	31.86337096	254.0360622	3.3	10.0	3600.0	1

Zs (surge/tidal waterlevel)	Hs (significant wave heigth [m])	Tp (peak period [s])	Mainang (wave angle of incidence) [degrees]	Gammajsp (jonswap peak factor) [-]	Dispersion angle [degrees]	Duration [s]	Dtbc+ (time step model) [s]
0.394872582	0.000743372	31.86337096	253.5956325	3.3	10.0	3600.0	1
0.416914804	0.000887871	31.86337096	252.9628251	3.3	10.0	3600.0	1
0.411738532	0.001057258	31.86337096	252.1013291	3.3	10.0	3600.0	1
0.385561863	0.001261243	31.86337096	251.0466569	3.3	10.0	3600.0	1
0.358498719	0.001513589	31.86337096	249.9417578	3.3	10.0	3600.0	1
0.329745308	0.001836548	21.97063133	248.8929907	3.3	10.0	3600.0	1
0.30476397	0.002257673	21.32386721	248.0158137	3.3	10.0	3600.0	1
0.292334616	0.002755166	20.92042355	247.4131374	3.3	10.0	3600.0	1
0.291336047	0.003350827	20.52288568	247.1195582	3.3	10.0	3600.0	1
0.299752631	0.004084004	20.22537935	247.3295853	3.3	10.0	3600.0	1
0.311366932	0.005227512	20.00714561	250.8261622	3.3	10.0	3600.0	1
0.319503127	0.044773052	0.932783943	274.5883897	3.3	10.0	3600.0	1
0.318242658	0.053373829	1.126200877	275.086996	3.3	10.0	3600.0	1
0.304526133	0.067522834	1.245783649	274.4222113	3.3	10.0	3600.0	1
0.276574614	0.081499852	1.364965164	273.2025254	3.3	10.0	3600.0	1
0.236262918	0.094193737	1.463018222	272.2179368	3.3	10.0	3600.0	1
0.185526313	0.107643038	1.552101814	271.3516648	3.3	10.0	3600.0	1
0.1292822	0.123082268	1.677872025	270.1713669	3.3	10.0	3600.0	1
0.079513533	0.142236248	1.80921098	268.6581834	3.3	10.0	3600.0	1
0.049116177	0.163340445	1.922877355	266.9836533	3.3	10.0	3600.0	1
0.045678562	0.187854479	2.044820075	265.9088344	3.3	10.0	3600.0	1
0.065059458	0.214740043	2.171569432	265.5106715	3.3	10.0	3600.0	1
0.102763819	0.249453063	2.277390882	265.1031093	3.3	10.0	3600.0	1
0.146018704	0.292144528	2.454552974	264.4979864	3.3	10.0	3600.0	1
0.192600045	0.343999903	2.653511371	264.0796616	3.3	10.0	3600.0	1
0.235801338	0.420426737	2.860367781	263.7891546	3.3	10.0	3600.0	1
0.2653948	0.525415938	3.115978088	263.0689601	3.3	10.0	3600.0	1
0.281795005	0.661702535	3.460164713	262.1110032	3.3	10.0	3600.0	1
0.282718394	0.854692461	3.85270342	261.1748459	3.3	10.0	3600.0	1
0.278295645	1.115243199	4.306166499	260.4933782	3.3	10.0	3600.0	1
0.283797374	1.443194233	4.816138277	260.1655991	3.3	10.0	3600.0	1
0.285208446	1.802437865	5.391956659	260.7456976	3.3	10.0	3600.0	1
0.297595759	2.107883299	5.959886404	262.224671	3.3	10.0	3600.0	1
0.329064417	2.394210422	6.499966157	263.4895534	3.3	10.0	3600.0	1
0.368833937	2.668625995	6.926219001	264.4769191	3.3	10.0	3600.0	1
0.41842037	2.941047753	7.429785585	265.2300624	3.3	10.0	3600.0	1
0.46380164	3.19028696	7.710914628	265.9204514	3.3	10.0	3600.0	1
0.494379288	3.403686212	8.123322503	266.6347357	3.3	10.0	3600.0	1
0.50741043	3.655333923	8.353995976	267.2371425	3.3	10.0	3600.0	1
0.507616647	3.927556284	8.818628965	267.8577276	3.3	10.0	3600.0	1
0.488078254	4.218953458	9.101725915	268.5917364	3.3	10.0	3600.0	1
0.457102836	4.562646239	9.407336572	269.4390163	3.3	10.0	3600.0	1
0.41733015	5.005024443	9.903590222	269.7223008	3.3	10.0	3600.0	1

Zs (surge/tidal waterlevel)	Hs (significant wave heigth [m])	Tp (peak period [s])	Mainang (wave angle of incidence) [degrees]	Gammajsp (jonswap peak factor) [-]	Dispersion angle [degrees]	Duration [s]	Dtbc+ (time step model) [s]
0.37364692	5.882397027	10.85157174	268.2630825	3.3	10.0	3600.0	1
0.339788469	7.025079423	11.79545532	268.1063849	3.3	10.0	3600.0	1
0.327656216	8.099294837	12.06068804	270.0625922	3.3	10.0	3600.0	1
0.330679296	8.849846539	12.2435481	273.4500637	3.3	10.0	3600.0	1
0.344557764	9.240089116	12.3248482	277.4687302	3.3	10.0	3600.0	1
0.367430767	9.36179894	12.33817485	281.804149	3.3	10.0	3600.0	1
0.373239584	9.336895642	12.28679882	286.3332627	3.3	10.0	3600.0	1
0.364515948	9.206042307	12.14756714	291.0922552	3.3	10.0	3600.0	1
0.345580498	8.966530816	12.00431445	296.107097	3.3	10.0	3600.0	1
0.317112762	8.62256306	11.94872318	300.4821275	3.3	10.0	3600.0	1
0.278474844	8.195269282	11.90804929	304.4548143	3.3	10.0	3600.0	1
0.243794955	7.760720268	11.89198083	307.8730984	3.3	10.0	3600.0	1
0.191688937	6.945242736	11.85555778	308.2687181	3.3	10.0	3600.0	1
0.170510463	6.325118077	11.75805317	309.8029385	3.3	10.0	3600.0	1
0.191229474	5.91989582	11.77477871	311.7630418	3.3	10.0	3600.0	1
0.229800988	5.623784235	11.84729738	313.5433356	3.3	10.0	3600.0	1
0.280381296	5.399263234	11.91082576	314.8709214	3.3	10.0	3600.0	1
0.338527604	5.214046171	11.93047526	315.7983914	3.3	10.0	3600.0	1
0.387381341	5.036293358	11.89068543	316.4588528	3.3	10.0	3600.0	1
0.419466668	4.843663384	11.78732906	316.968415	3.3	10.0	3600.0	1
0.445219541	4.627273569	11.57794224	317.4867255	3.3	10.0	3600.0	1
0.453290846	4.381675888	11.35636046	318.1692817	3.3	10.0	3600.0	1
0.447005189	4.115462947	11.16680656	319.0127977	3.3	10.0	3600.0	1
0.419373805	3.853632855	10.9745312	319.9067288	3.3	10.0	3600.0	1
0.370476312	3.628345497	10.76964349	320.8252469	3.3	10.0	3600.0	1
0.314855331	3.445042935	10.60297428	321.6060289	3.3	10.0	3600.0	1
0.277179347	3.286776152	10.52953341	322.086284	3.3	10.0	3600.0	1
0.263210337	3.143586086	10.50761162	322.3175666	3.3	10.0	3600.0	1
0.27000108	3.010889934	10.50243666	322.3815213	3.3	10.0	3600.0	1
0.28814893	2.887887484	10.49913313	322.36022	3.3	10.0	3600.0	1
0.304304352	2.770568376	10.49841056	322.2833767	3.3	10.0	3600.0	1
0.309882143	2.656754579	10.5002874	322.1508389	3.3	10.0	3600.0	1
0.298032709	2.546508794	10.50467938	321.9712531	3.3	10.0	3600.0	1
0.272770828	2.439560895	10.51090974	321.7270922	3.3	10.0	3600.0	1
0.237262377	2.337724531	10.52763878	321.4149177	3.3	10.0	3600.0	1
0.190525826	2.240847433	10.56403671	321.0151883	3.3	10.0	3600.0	1
0.148806064	2.153522496	10.6167784	320.6493842	3.3	10.0	3600.0	1
0.121991405	2.076387092	10.67014347	320.35845	3.3	10.0	3600.0	1
0.111731978	2.007264141	10.71038852	320.1140143	3.3	10.0	3600.0	1
0.124985095	1.944069588	10.74541444	319.8929959	3.3	10.0	3600.0	1
0.162825144	1.885369026	10.77318321	319.6747545	3.3	10.0	3600.0	1
0.217943524	1.830094142	10.79415769	319.4321092	3.3	10.0	3600.0	1
0.278120747	1.782106801	10.80959831	319.3502509	3.3	10.0	3600.0	1

Zs (surge/tidal waterlevel)	Hs (significant wave heigth [m])	Tp (peak period [s])	Mainang (wave angle of incidence) [degrees]	Gammajsp (jonswap peak factor) [-]	Dispersion angle [degrees]	Duration [s]	Dtbc+ (time step model) [s]
0.332981068	1.741367264	10.81935471	319.3878181	3.3	10.0	3600.0	1
0.378898481	1.704871578	10.82176719	319.4188341	3.3	10.0	3600.0	1
0.414705434	1.670964205	10.81599906	319.3713284	3.3	10.0	3600.0	1
0.437210038	1.638680183	10.80438553	319.2243557	3.3	10.0	3600.0	1
0.438200529	1.60723766	10.79130334	318.9723415	3.3	10.0	3600.0	1
0.412528916	1.577552322	10.78158572	318.7404792	3.3	10.0	3600.0	1
0.36769995	1.550137642	10.77708914	318.5981045	3.3	10.0	3600.0	1
0.311720006	1.523414972	10.77683292	318.5271104	3.3	10.0	3600.0	1
0.267462358	1.496482574	10.77753292	318.5291246	3.3	10.0	3600.0	1
0.253747399	1.469236098	10.77454633	318.6008715	3.3	10.0	3600.0	1
0.267816406	1.443235956	10.76302117	318.7990424	3.3	10.0	3600.0	1

F. UNIBEST CL+

UNIBEST CL+ is an abbreviation for Uniform Beach Sediment Transport, which is developed by WL-Delft Hydraulics. This empirical based model is designed for the long-term simulation of coastal evolution due to changes in longshore sediment transport. Within UNIBEST CL+ two sub-modules are defined: The Longshore Transport module (LT-module) and the CoastLine module (CL-module). The LT-module calculates the wave and tide induced longshore current and the related sediment flow for certain cross-sections along the coast. The output is used by the CL-module to simulate the coastal shoreline evolution over time. To do so, a uniform time-invariant beach slope is assumed based on the single line theory. According this theory, the coastal shoreline evolution relies on the along shore sediment flux, assuming a stable coastal profile. A clarification is given in figure F1. (Slott, 2008). Hard structures such as groynes, breakwaters and revetments can be included in the CL-module.

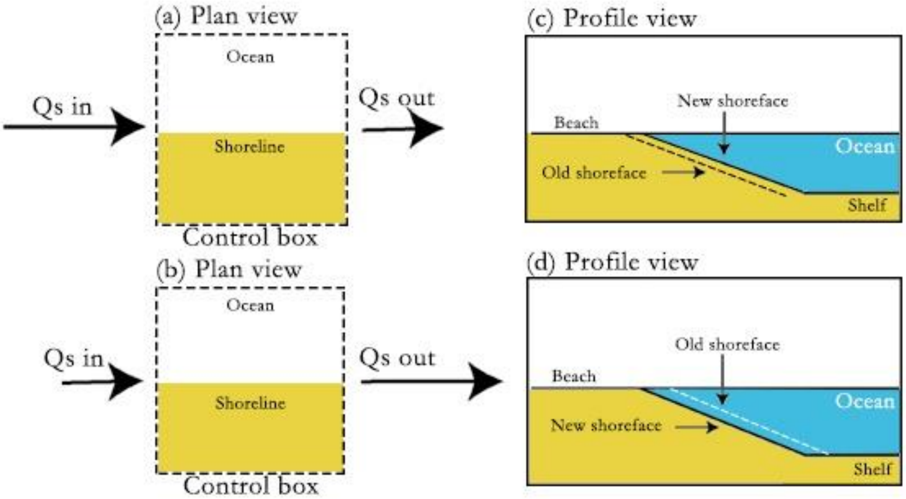


Figure F1. Clarification of the coastal shoreline evolution

Model set up LT-module:

The Bijker formula is used for computing the sediment transport along the Oasis beach, as was recommend by (EROSION OF THE HICACOS PENINSULA 2003). Furthermore, the averaged cross-section is used for representing the total Oasis beach and no wind and tidal influence is considered, see figure F2. A rock layer can be included in UNIBEST when implementing a smaller value to the truncation transport coordinate than to the dynamic boundary. However, this is not done as the nourished profile is used in calculations, which has a significant sand layer cover the rocks. The model input is summarized in table F1.

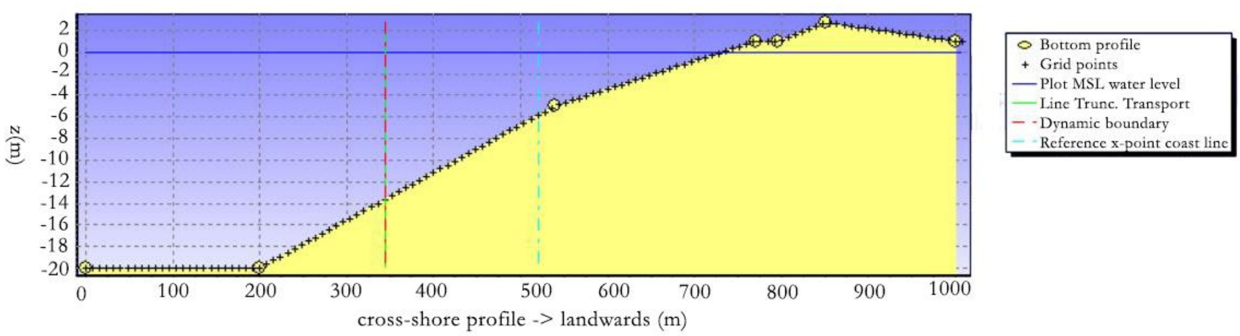


Figure F2. Representative cross-shore profile UNIBESTL CL+

Table F1. Input parameters UNIBEST LT-module

Cross-shore profile	value	unit	Wave parameters	value	unit
reference x-point coastline	520	[m]	coefficient for wave breaking (gamma)	0.8	[-]
X-point dynamic boundary	340	[m]	coefficient for wave breaking (alfa)	1	[-]
X-point truncation transport	340	[m]	coefficient for bottom friction	0.01	
reference level	0	[m]	value of the bottom roughness (kb)	0.05	
Transport parameters			Wave current		
D50	660	[µm]	H0	0	[m]
D90	1100	[µm]	Hsig	2.1	[m]
sediment density	2700	[kg/m3]	period	7.67	[s]
seawater density	1022	[kg/m3]	alfa	315	[-]
porosity	0.4	[-]	duration	350	[days]
bottom roughness	0.045	[m]	H0	0	[m]
sediment fall velocity	0.11	[m/s]	Hsig	0.513	[m]
criterion deep water, Hs/h	0.07	[-]	period	4.32	[s]
coefficient deep water, B	2	[-]	alfa	67.9	[-]
criterion shallow water, Hs/h	0.6	[-]	duration	15	[days]
coefficient shallow water, B	5	[-]	Active height	5.0	[m]
Coastal orientation	10	[°]			

Model set up CD-module:

Influence of the Paso Malo:

The coastal dynamics are simulated during 5 years with coastal response output 5 times a day, taken normal and cold front conditions into account. To reduce errors, a wide grid is used for simulating the influence of the channel, see figure F3.

Figure F3. The grid for simulation of the influence of the channel

Run specifications:

The simulation time covers a time span of five years, with five time steps a day. The used representative characteristics are shown in table F2 and shortly described.

Global transport: according to the Institute of Oceanology the global transport along the Peninsula de Hicacos is 50,000 m3/year, which is used as a source near the right boundary. Boundary conditions: a rock layer is found at the surface near the left boundary from the Oasis beach. Simulating this non-erosive layer, a constant shoreline is assumed. For the right boundary, located about 2 kilometres Eastwards from the Paso Malo, a constant coastal angle is assumed as no significant gradients are preferred at the edge of the computational grid. Groynes: To model the entrance of the Paso Malo, a groyne is placed at the location of the Western side of the channel. Whereas the coastline in reality would become interrupted, a simplified constant beach is assumed in the model.

Revetments: Beneath the sandy beaches along the modelled coastline a rock layer is present. This is incorporated in the model by limiting the maximum coastal erosion due to revetment placed along the coast. The revetment is located around 50 metres from the shoreline.

Table F2. Runs specifications UNITBEST CD-module.

day from	day to	Global transport	Boundary conditions	Groynes	Revetments
0	15	50,000 [m3/year]	R: constant Y; L: constant coastal angle	Paso Malo	Along whole coastline
15	365	50,000 [m3/year]	R: constant Y; L: constant coastal angle	Paso Malo	Along whole coastline

G. XBeach input parameters

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% XBeach parameter settings input file
%%% date: 17-10-2018
%%% Model No.: 5.0
%%% Location: Oasis Beach section
%%% Standard: Nourishment 40 metres + Paso Malo groyne + Western Groyne
%%% Model specs: Cold front conditions, Coral reef added
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Grid parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
depfile = bathyMetryM45611.dep
nx = 159
ny = 109
alfa = 355
thetanaut = 1
thetamin = -90
thetamax = 90
dtheta = 15
vardx = 1
gridform = delft3d
xyfile = XBeachgrid510.grd

%%% Hydrodynamic options %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
wavemodel = surfbeat
morfacopt = 1
morfac = 10

%%% Model time%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tstart = 0
tintg = 1800
tstop = 432000

%%% Physical parameters%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
rho = 1023
```

```
%%% Tide boundary conditions%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tideloc        = 1
tidetype       = instant
zs0file        = Tidenormallong.txt


%%% Wave boundary condition parameters%%%%%%%%%%%%%%%%%%%%%%%%
instat         = 4
bcfile         = jonswapCF.txt
lateralwave    = wavecrest


%%% Granular%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fw             = 0.6
fwcutoff       = 2.3
D50            = 0.9E-3
D90            = 1.5E-3
rhos           = 2700
wetslp         = 0.150000
dryslp         = 1
struct         = 1
bedfriction    = cf
bedfricfile    = cf_coral.dep
ne_layer       = ne_layer_M456.dep
```

```
%%% Output variables%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
outputformat = netcdf
nglobalvar = 19
H
zs
zb
ue
ve
Fx
Fy
ccg
Susg
Subg
Svsg
Svbg
E
D
depo_ex
Df
dzav
kb
sedero
```

H. Evacuation transport model

General assumptions and input

The design of the simulation is showed in figure H1.

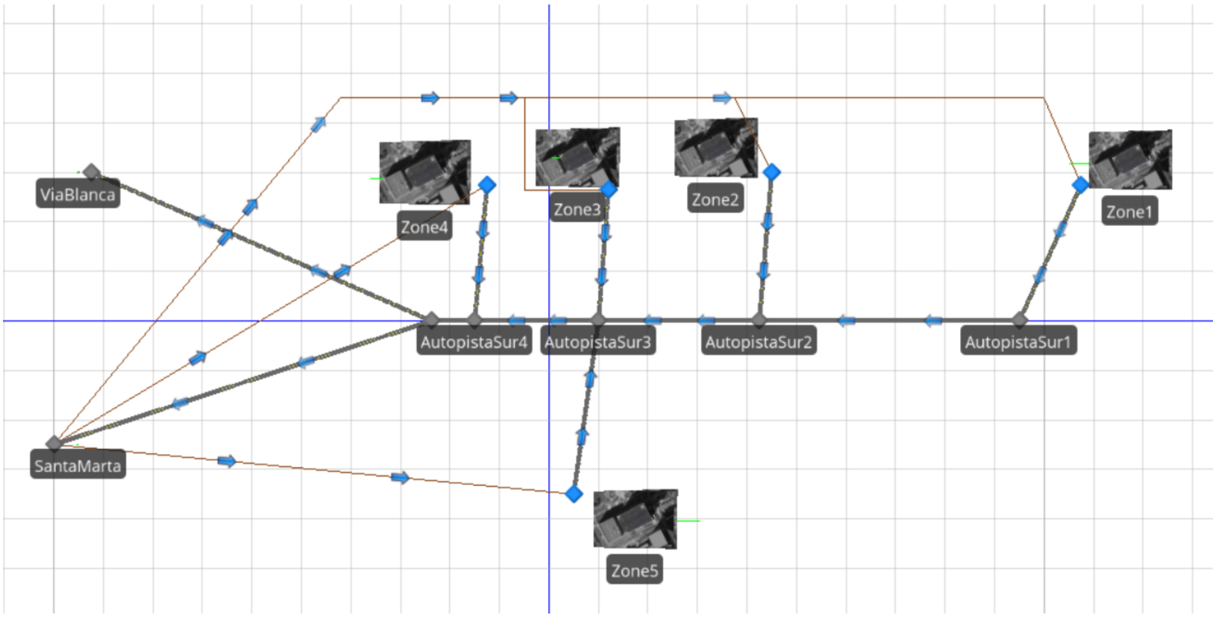


Figure H1: Simio Simulation design

Population

The population is known and as stated in section 3.5.3 consists of the inhabitants of Varadero town, the employees in tourist facilities and the beach tourists. In the model, the population is divided into two groups: locals and tourists. These groups are chosen based on the way they are transported. There are a few tourists in Varadero using a rental car, but most of them are transported by bus. Therefore, it is chosen to neglect the cars and to transport all tourists by buses, because that is the most efficient way to evacuate large groups. On the contrary, locals can be transported by both buses and smaller. They often use taxis or the bus to transport themselves for one location to another and therefore also assumed in the simulation model.

The number of locals and tourists is set on the number of daily trip generation as calculated in Section 2.2.1 and is changed in every experiment according to the type of situation, this could thus be the current situation or one of the three future situations (table H1).

Table H1. Number of population in the four situations.

	Yearly	Daily	2048	Yearly		2048	Daily	
Purpose			MinTur	Financial	Linear	MinTur	Financial	Linear
Inhabitants	20,689	20,689				21,208	21,208	21,208
Work		37,000				47,000	47,000	47,000
Tourism	1,700,000	39,842	8,800,000	6,000,000	3,200,000	210,000	140,000	75,000
Total	**1,720,689**	**97,581**	**8,800,000**	**6,000,000**	**3,200,000**	**278,208**	**208,208**	**143,208**

Zones

The population is divided into the five different zones. This is done based on the location of hotels and houses on the peninsula. An overview of the Distribution is given in the table below.

Table H2. The distribution of the population among the five zones

Zone	Distribution of populations
1	30% of tourists + 20% locals (20% employees)
2	20% of tourists + 25% locals (13% inhabitants + 12% employees)
3	20% of tourists + 25% locals (12% inhabitants + 13% employees)
4	30 % of tourist + 26% locals (6% inhabitants + 20% employees)
5	4 % locals (4% inhabitants)

Vehicles

The population is transported by either buses or cars. They both have a fixed route from a certain zone to one of the two destination nodes, Santa Marta or Via Blanca (see figure I2 for an example). To clarify the simulation model is decided to not let the vehicles return to their zones over the Autopista Sur, which would happen in reality. The vehicles are returned to their zones over fictional road with the same length and speed limit as the Autopista Sur.

As described in Section 2.2.3 there are only 38 out of 1000 people in Cuba owning a vehicle and 60% of all trips are made with buses. Furthermore, as mentioned in section 2.2.4 is 20% of the road in normal circumstances used by buses and it is assumed that this percentage could to 50% in case of evacuation.

	Sequence
1	Output@Zone2
2	AutopistaSur2
3	AutopistaSur3
4	AutopistaSur4
5	Bifurcation
6	Input@SantaMarta

Figure H2. The fixed route for buses en cars from zone 2 to destination.

Roads

The peninsula has a length of 22 kilometres, the town Varadero ends after approximately 10 kilometres. That is why the highway Autopista Sur in the simulation model is 10 kilometres in total, from node AutopistaSur1 till node AutopistaSur4, and the speed limit is set to 100 km/h. The average distance to zone 1 is 5 kilometres, because it contains the latter half of 10 kilometres. The zones are connected to the Autopista Sur by local roads with a speed limit of 50 km/h. The distances between the Autopista Sur and zones 2,3 and 4 are rather small and estimated as respectively 500, 300 and 500 metres. Zone 4 has a distance of 1 kilometres to the Autopista Sur because it also includes the part at the beginning of the peninsula between the sea and Paso Malo where there is more distance to the Autopista Sur. The distance from the peninsula to Santa Marta and Via Blanca is set on 3 kilometres. As mentioned in section 2.2.4 the capacity of the local roads is not considered, but the other roads in the simulation model are set to the maximum capacity given in section 2.2.4.

I. Results XBeach simulations

In this appendix the results of every model simulated in XBeach is represented. Per model are written what the input variables, the parameters and the most notable outcomes are.

Model Number: 1.0

Model Title: Zero-reference N

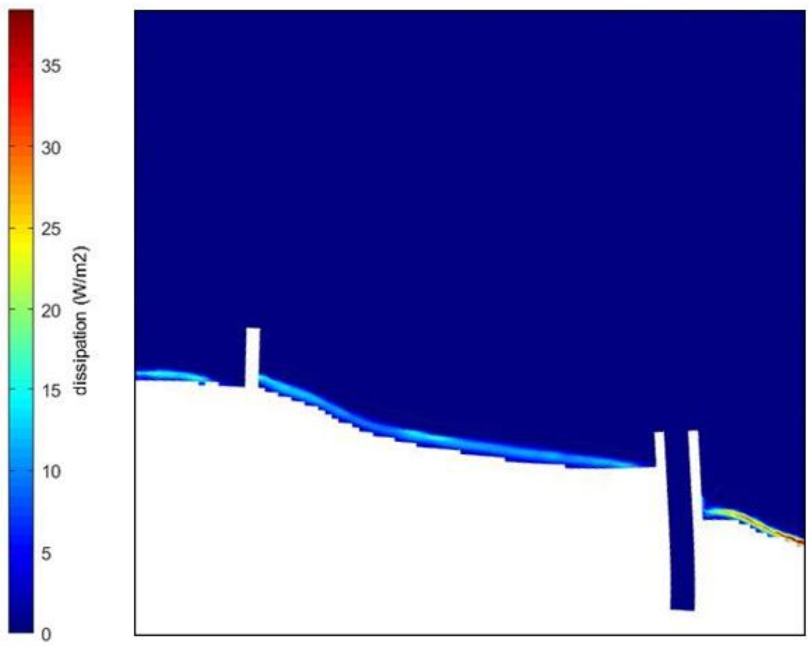
Conditions modelled: Normal conditions

Bathymetry type:
Nourished bathymetry, no coral

Present Structures:

- Paso Malo groyne
- Western groyne

Wave dissipation figure:

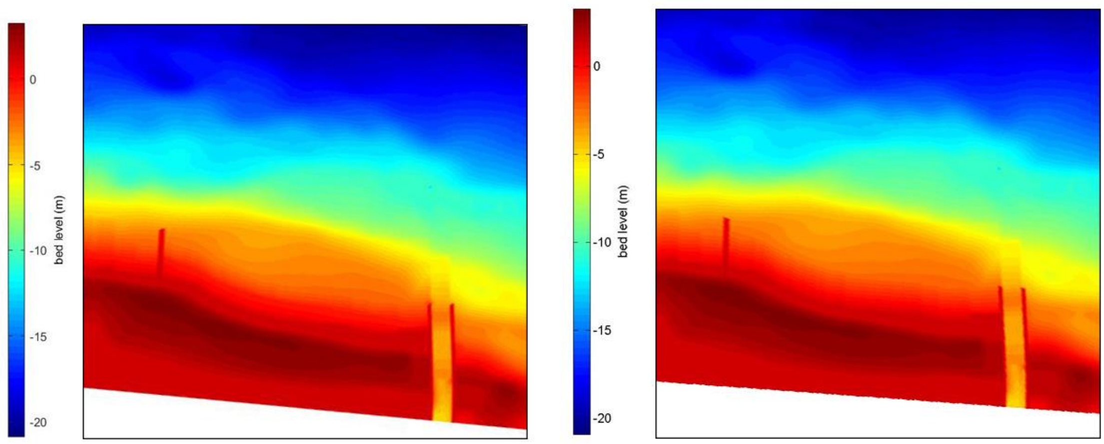


Key parameters: H_s = 0.51 m T_p = 4.32 s β = 68° (nautical)

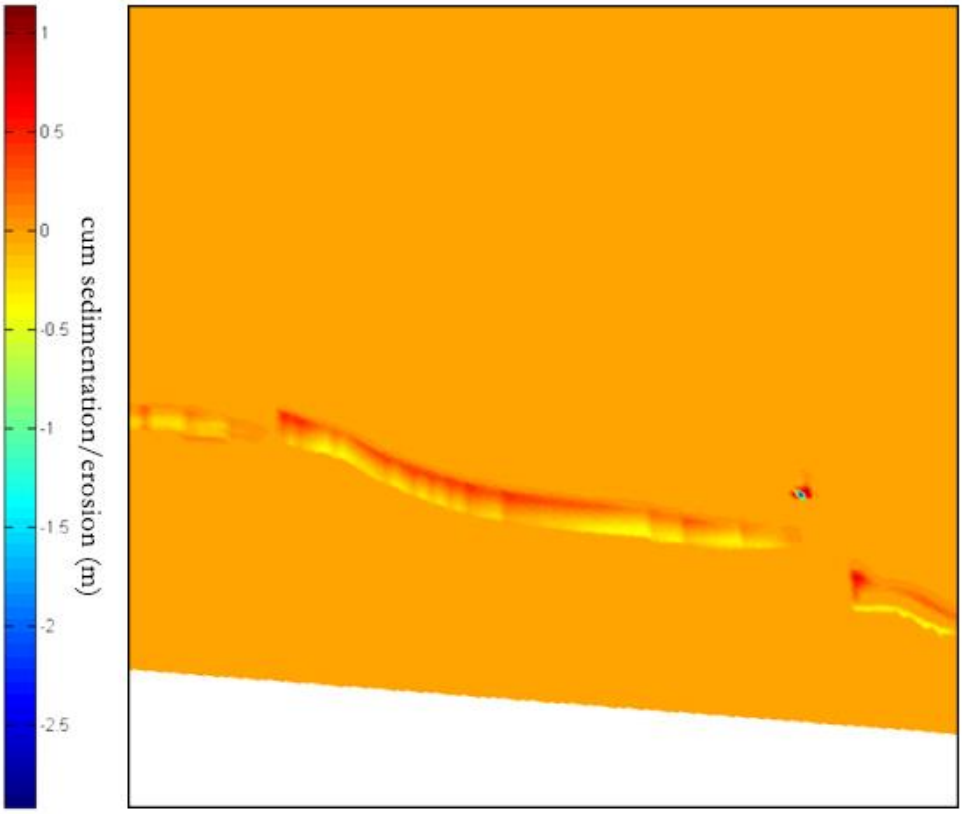
Input files:
XBeachgrid510.grd
bathymetryM123.dep
jonswapN.txt
ne_layerM123.dep
TidenorMalong.txt

Errors/Cut-offs: None

Bed levels before and after simulation:



	Observations	Discussion
1.	Slope flattening	The 1:20 beach slope is flattened by small offshore transport between the waterline during low and high tide. During the five days modelled this resulted in a maximum bottom level decrease of 0.4 metres.
2.	Alongshore transport fully blocked	Westward longshore transports because of the incoming waves from the northeast is blocked by the new groyne.
3.	Shoreline reorientation	Due to the westward alongshore sediment transport being blocked at the west end of the Oasis section. The shoreline is turning to be perpendicular to the wave direction. This effect is expected to stabilize over timespans.
4.	Scour at Paso Malo groyne	At the end of the western Paso Malo groyne a scour hole with a depth of approximately 1.0 metre develops in the first five days of this new situation. The visualisation is a zoomed in top view of the cumulative erosion/accretion over five days. The Paso Malo groyne lies below the scour hole

	Visualisations for discussion
4.	

Model Number: 2.0

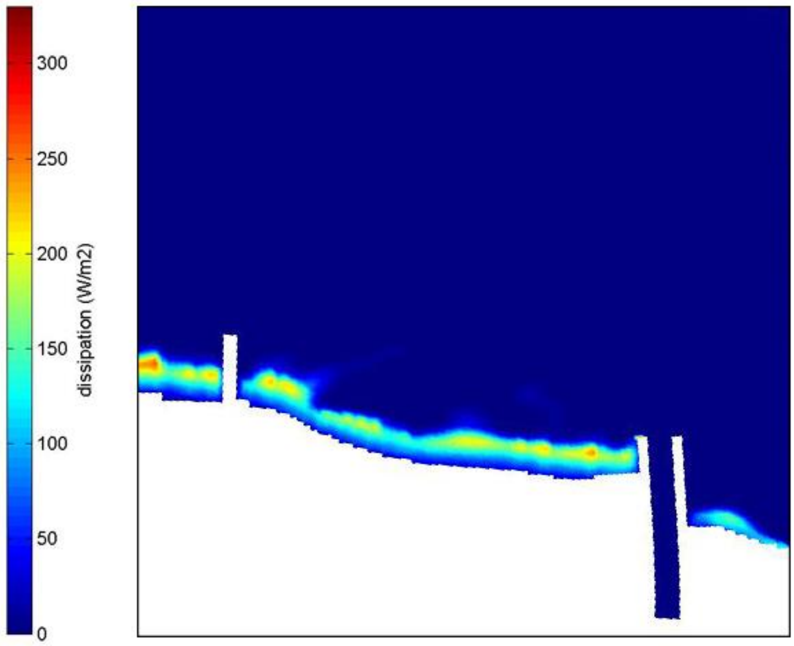
Model Title: Zero-reference CF

Conditions modelled: Cold front conditions

Bathymetry type:
Nourished bathymetry, no coral

Present Structures:

- Paso Malo groyne
- Western groyne

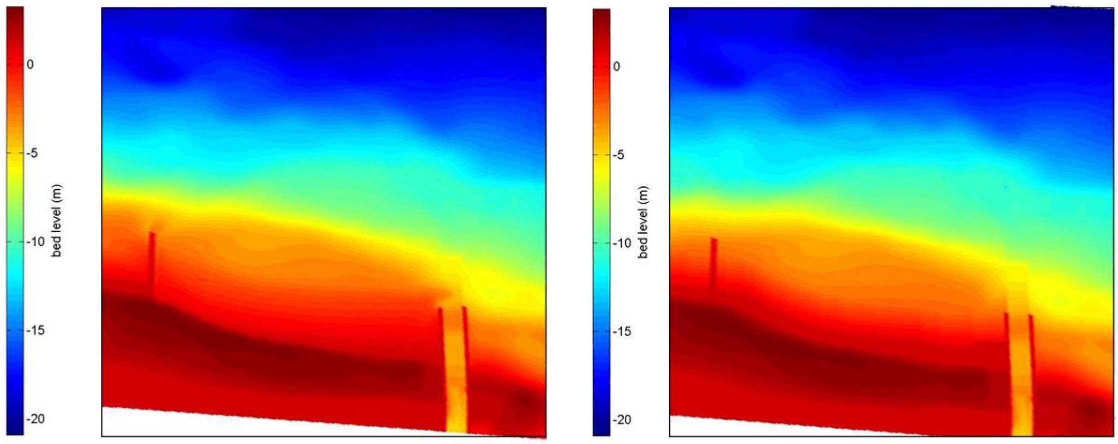


Key parameters: H_s = 2.10 m T_p = 7.67 s β = 315° (nautical)

Input files:
XBeachgrid510.grd
bathymetryM123.dep
jonswapCF.txt
ne_layerM123.dep
TidenorMalong.txt

Errors/Cut-offs: None

Bed levels before and after simulation:



	Observations	Discussion
1.	Larger scale slope flattening	A similar effect occurs as described in observation 1 of the previous model. The scale here is different. Erosion rates exceed 1.0 metre and the sedimentation occurs further from the dry shore. This sediment is likely lost, as it is deposited at the steeper foreshore between 3 and 5 metres depth.
2.	Eastward transport	Relatively large eastward transport rate w.r.t. westward transport in normal conditions.
3.	Alongshore transport not fully blocked	The eastward transport passes the Paso Malo groyne in significant amounts, causing a loss of sediment volume in the Oasis beach sector.
4.	Siltation of Paso Malo entrance	At the entrance of the Paso Malo groyne, sediment is deposited by the alongshore current, leading to a siltation the harbour entrance. Bed levels rise approximately 1.0 metres.

Model Number: 3.2

Model Title: Zero-reference Hurricane Irma

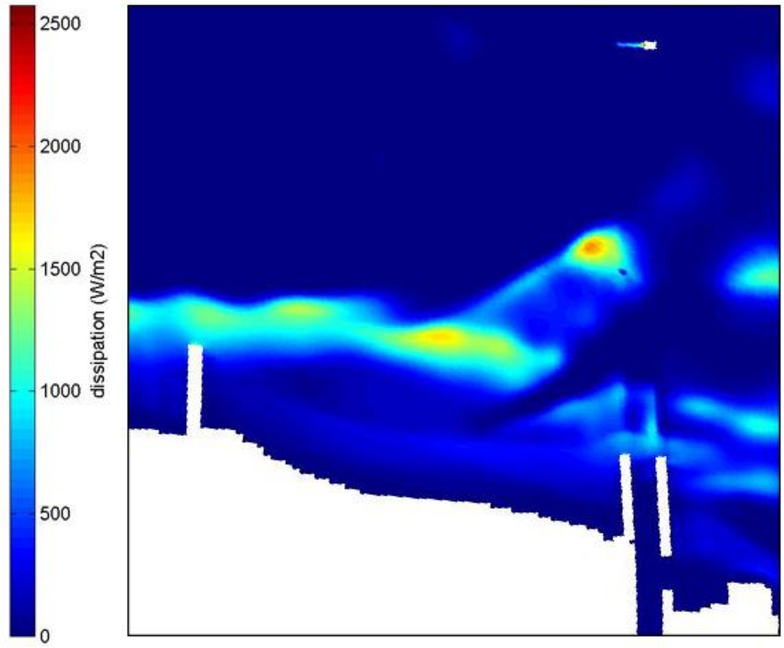
Conditions modelled: Hurricane Irma

Bathymetry type:
Nourished bathymetry, no coral

Present Structures:

- Paso Malo groyne
- Western groyne

Wave dissipation figure:

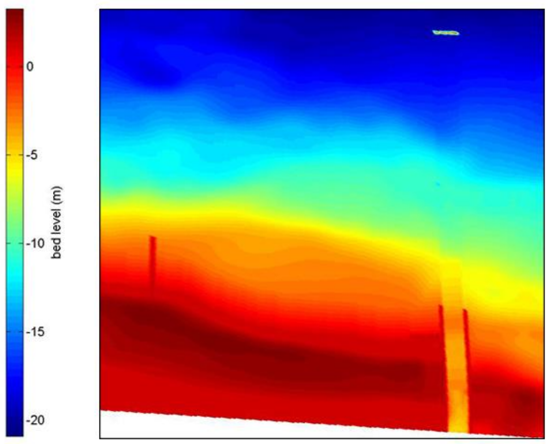


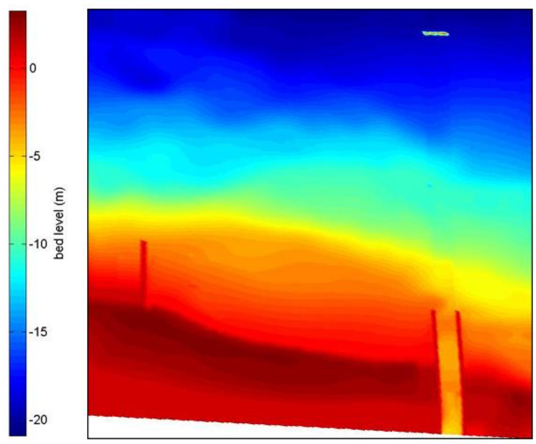
Key parameters (time-varying):
$0.514 > H_s > 9.34$ m
$4.32 > T_p > 22.0$ s
$285° < \beta < 322°$ (nautical)

Input files:
XBeachgrid510.grd
bathymetryM123.dep
ne_layerM123.dep
filelistIRMA.txt
jonswapI48-120.txt (73 files)
TideIlong.txt

Errors/Cut-offs: None

Bed levels before and after simulation:





	Observations	Discussion
1.	Peak wave intensity passes before the model cuts off.	The highest intensity waves erode the beach almost completely and after 60 hours (out of 72 modelled), after peak intensity, the model registers complete erosion and shuts off. See visualisation.
2.	Early storm shows similar behaviour as cold fronts.	Sediment is transported offshore and deposited around the five-metre depth contour, which also happens during cold fronts. Once the wave height increases further (larger than 3 metres) the sediment is transported further down the steep foreshore and is not replaced naturally.
3.	Large energy dissipation outside shielded area.	Due to the WNW direction from which the waves come in and the large wave height, most wave energy does not reach the nourished beach, though still causing complete erosion.

Model Number: 4.1

Model Title: Coral reef performance normal

Conditions modelled: Normal conditions

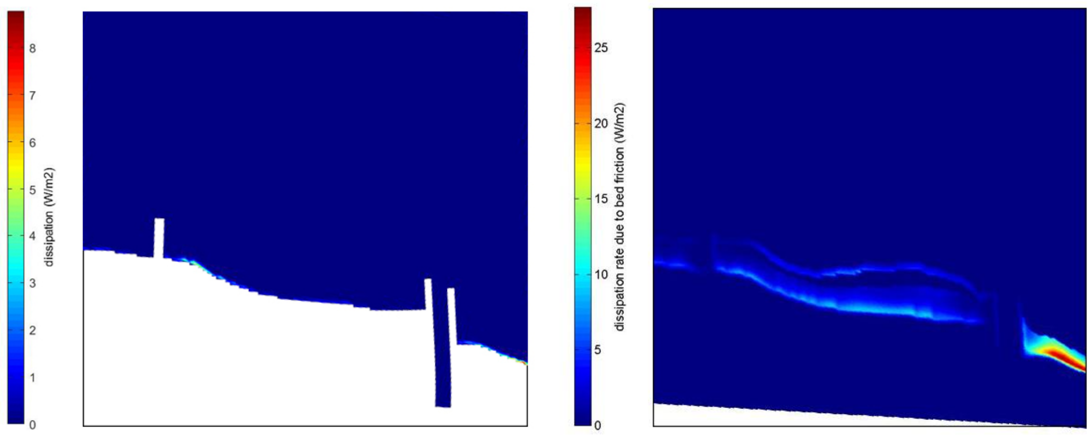
Bathymetry type:

Nourished bathymetry including coral reef

Present Structures:

- Paso Malo groyne
- Western groyne
- Reef blocks

Wave dissipation and bed friction dissipation:



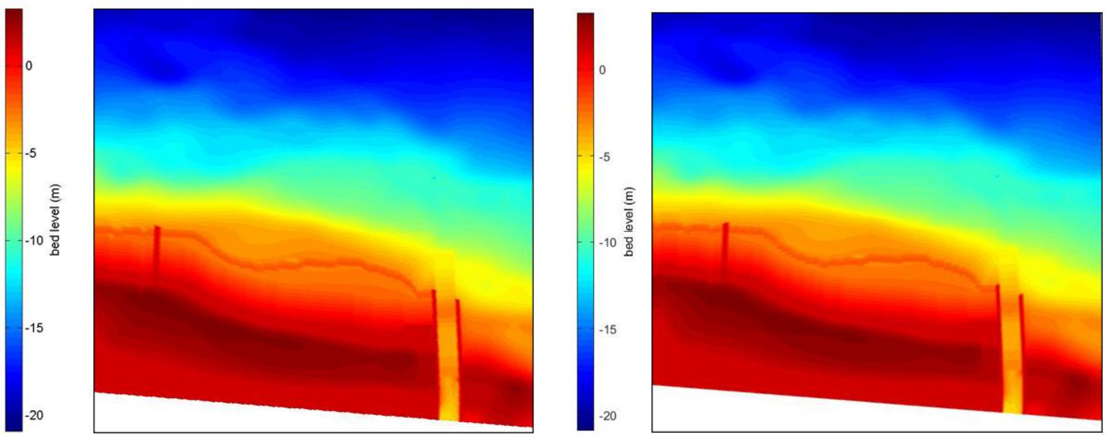
Key parameters: $H_s = 0.51$ m $T_p = 4.32$ s $\beta = 68°$ (nautical)

Input files:

XBeachgrid510.grd
bathymetryM45612.dep
cf_coral.dep
jonswapN.txt
ne_layerM456.dep
TidenorMalong.txt

Errors/Cut-offs: None

Bed levels before and after simulation:



	Observations	Discussion
1.	Reduced slope flattening	As compared to the normal condition run (model number 1) the cross-shore transport is significantly reduced from 0.4 metre to less than 0.05 metres over most of the Oasis beach. A maximum bed level change of 0.05 metres is observed in the lee side of the Paso Malo groyne.
2.	Alongshore transport reduction	Westward longshore transport is reduced significantly, resulting in bed changes smaller than 0.01 m. As a result of this reduction, shoreline reorientation is no longer observed, as was the case in model 1.
3.	Scour at Paso Malo groyne	At the end of the western Paso Malo groyne a scour hole with a depth of approximately 1.0 metre develops in the first five days of this new situation.

Model Number: 5.1

Model Title: Coral reef performance cold front

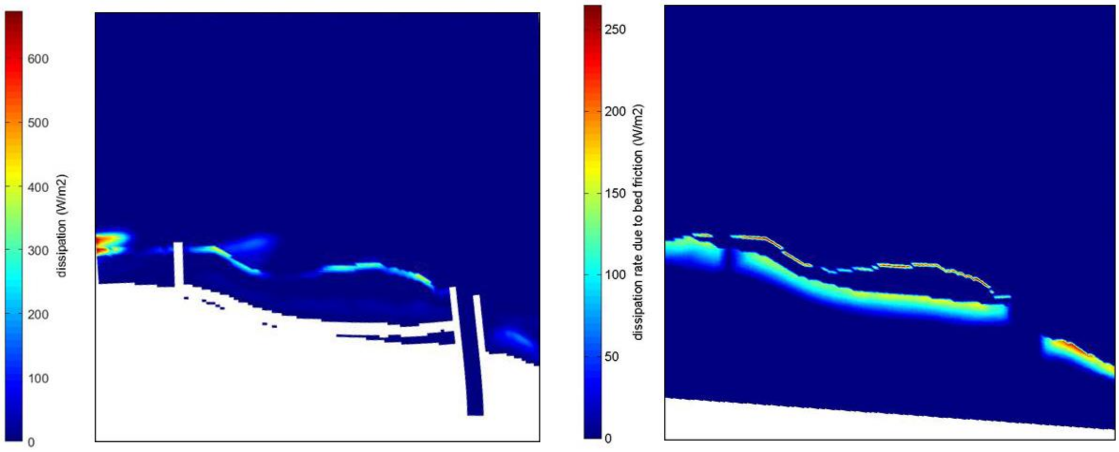
Conditions modelled: Cold front conditions

Bathymetry type:
Nourished bathymetry, coral reef

Present Structures:

- Paso Malo groyne
- Western groyne
- Reef blocks

Wave dissipation and bed friction dissipation:

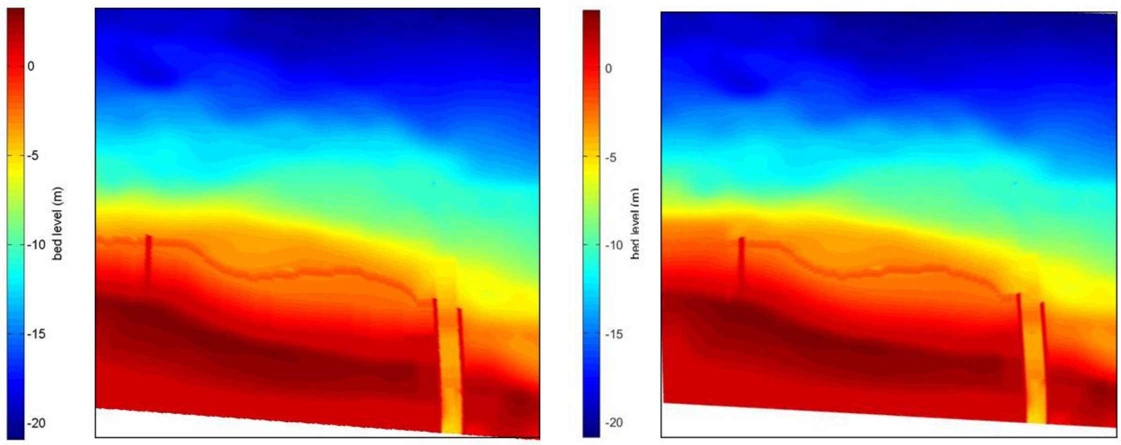


Key parameters: $H_s = 2.10$ $T_p = 4.67$ $\beta = 315°$ (nautical)

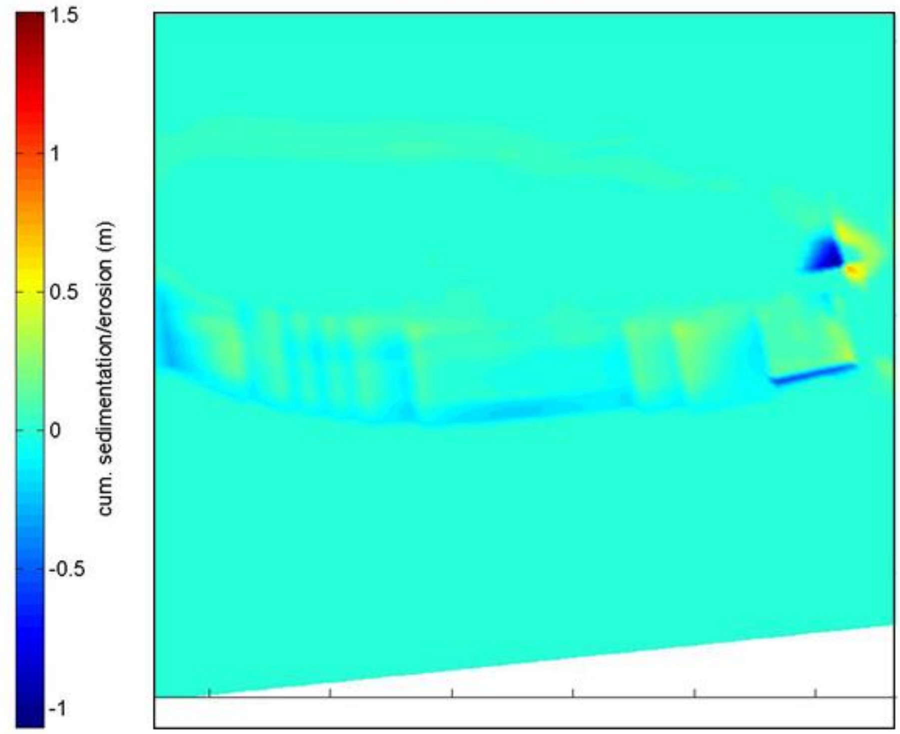
Input files:
XBeachgrid510.grd
bathymetryM45612.dep
cf_coral.dep
jonswapCF.txt
ne_layerM456.dep
TidenorMalong.txt

Errors/Cut-offs: None

Bed levels before and after simulation:



	Observations	Discussion
1.	Eastward transport	As compared to model 2, the coral reef significantly reduces the bed level change due to alongshore transport from 1.5 metres to a maximum of 0.4 metres. The
2.	Alongshore transport significantly reduced	The loss of sediment passing the Paso Malo groyne is reduced to nearly zero. Where the situation in model 2, without the coral reef, shows a significant sedimentation in the Paso Malo channel, the coral reef blocks sediment outflow from the shallow zone (depths smaller than three metres).
3.	Remarkable sedimentation/erosion pattern	The resulting erosion/accretion pattern alternates between erosion and accretion in alongshore direction (see visualisation). It is expected that this is caused by the somewhat patchy method used to model the coral and that the transport is in reality more or less constant over the Oasis sector (only influenced by local shoreline orientation).
4.	Scour at Paso Malo groyne	At the end of the western Paso Malo groyne a scour hole with a depth of approximately 4.0 metres develops in the first five days of this new situation.

	Visualisations for discussion
3.	

Model Number: 6.2

Model Title: Coral reef performance during hurricane Irma

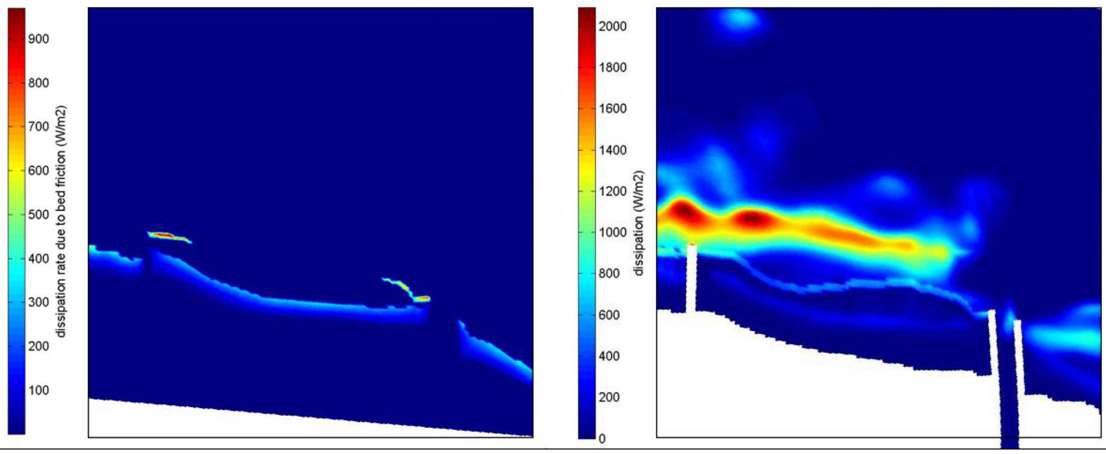
Conditions modelled: Hurricane Irma

Bathymetry type:
Nourished bathymetry, coral reef

Present Structures:

- Paso Malo groyne
- Western groyne
- Reef blocks

Wave dissipation and bed friction dissipation:

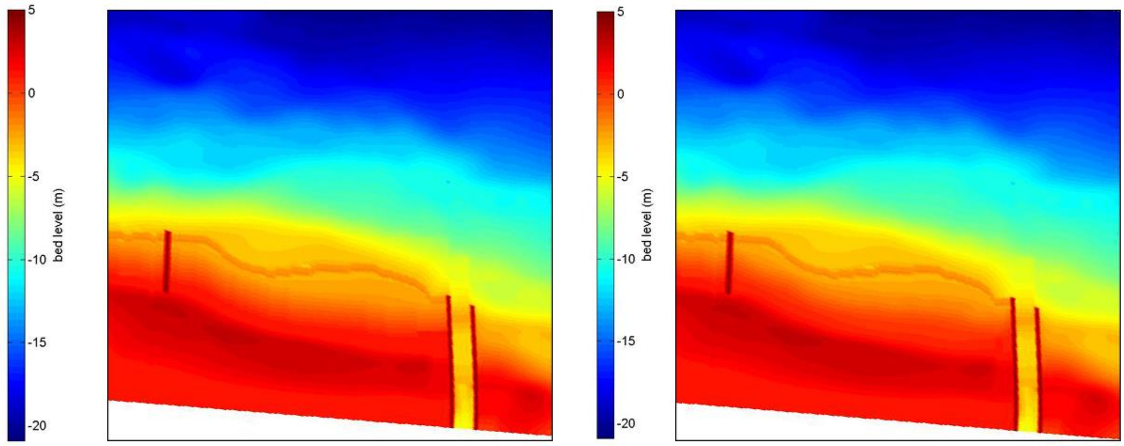


Key parameters (time-varying):
0.514 > H_s > 9.34 m
4.32 > T_p > 22.0 s
285° < β < 322° (nautical)

Input files:
ne_layer_M456.dep
bathymetryM45612.dep
jonswapI48-120.txt (73 files)
cf_coral.dep
tideIlong.txt
XBeachgrid510.grd

Errors/Cut-offs:
As the first model indicated excessive flow over the Paso Malo groyne, the groyne was altered as if it was 5.0 m above water level. This made the model stable, and as the groyne is impermeable and overflow does not occur (though significant overtopping does), this is not expected to alter the model outcome significantly.

Bed levels before and after simulation:



	Observations	Discussion
1.	Little wave energy reaches the shallow zone	The largest storm waves pass in eastward direction along the 5.0 metre depth contour. This means that only a small part of the wave energy reaches the shallow beach zone, causing smaller sediment transports than expected. As can be expected with a wave direction from the WNW, the east section of the Oasis beach is hit the hardest.
2.	Friction dissipation of reef relatively small	Depth induced breaking accounts for more than three times the energy loss than friction dissipation, though for larger waves, the effect of friction dissipation is larger, taking the most energy from the largest waves.
3.	Large local bed level changes	The bed level changes over the duration of hurricane Irma are significant, reaching up to 1.2 metres in erosion (local scour at the tip of the Paso Malo), but along the Oasis beach, only rarely exceed 0.4 metres (only near the Paso Malo groyne).

Model Number:	7.1
Model Title:	Enclosed beach Cold front
Conditions modelled:	Cold front conditions

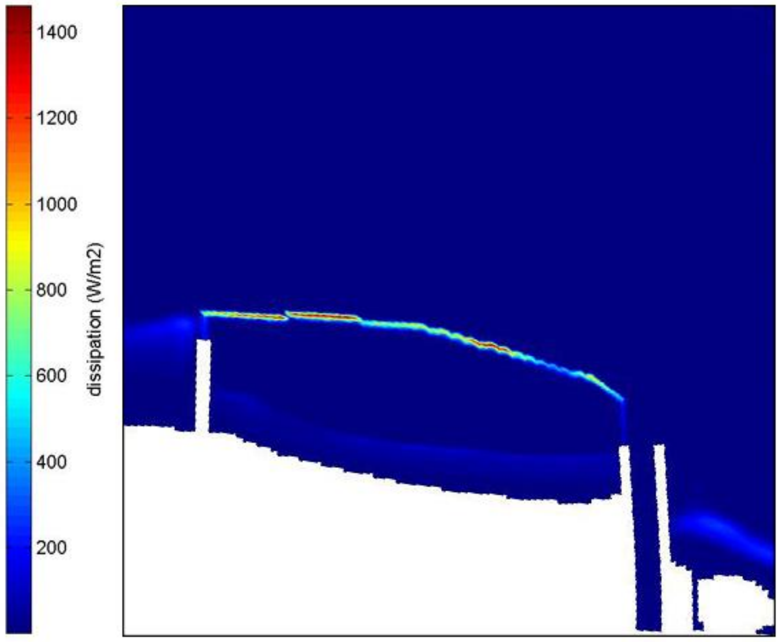
Bathymetry type:

- Nourished bathymetry, coral reef

Present Structures:

- Extended Paso Malo groyne
- Extended western groyne
- Submerged breakwater

Wave dissipation figure:

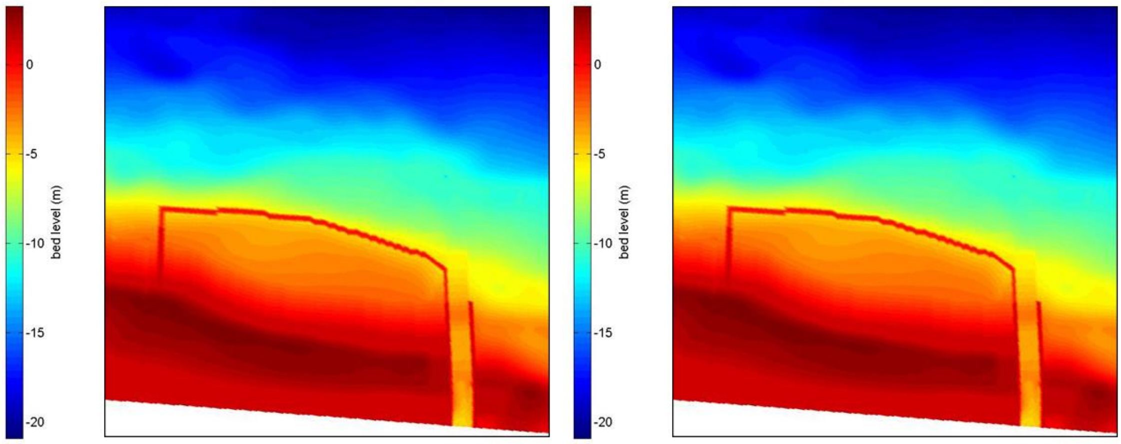


Key parameters: $H_s = 2.10$ $T_p = 7.67$ $\beta = 315°$ (nautical)

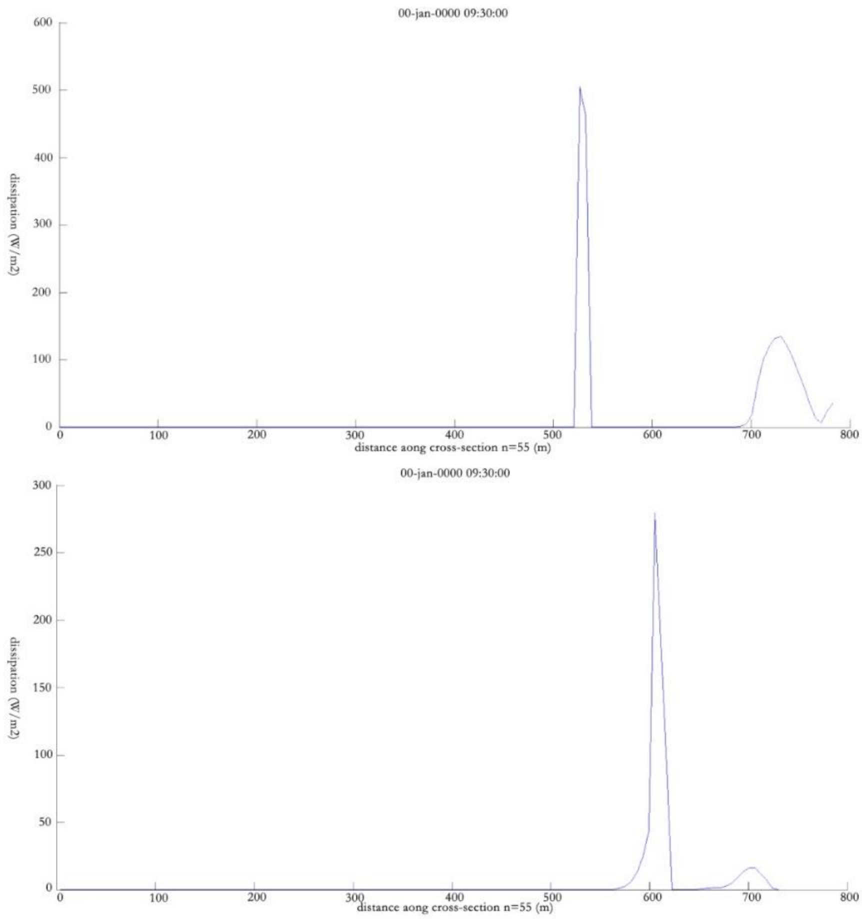
Input files:
BathymetryM7813.dep
jonswapCF.txt
TidenorMalong.txt
Ne_layer_M78910.dep

Errors/Cut-offs: None

Bed levels before and after simulation:



	Observations	Discussion
1.	Eastward transport	As indicated in model 2 and 5, the cold fronts cause an eastward alongshore transport of sediment.
2.	Alongshore transport significantly reduced	The loss of sediment passing the Paso Malo groyne is reduced to zero, due to the breaking of waves on the breakwater, which lies further offshore than the coral reef. Even the scour hole near the Paso Malo groyne is stopped from developing, due to the presence of the groyne extension.
3.	Remarkable sedimentation/erosion pattern	The varying alongshore sedimentation/erosion pattern as observed in model 5 is somewhat less clear, but still present here. It seems the wave energy dissipation varies somewhat for the location alongshore.
4.	Total sedimentation/erosion	The breakwater and extended groynes result in a maximum erosion of approximately -0.8 metres in the west end of the Oasis beach but result in an accumulation of 1.2 metres near the Paso Malo groyne. This is a relatively large difference, compared to the 0.4 metres found using the coral reef. The wave dissipation corresponding to both situations is shown in the visualisation.

	Visualisations for discussion
4.	

Model Number: 8.1

Model Title: Enclosed beach hurricane Irma

Conditions modelled: Hurricane Irma

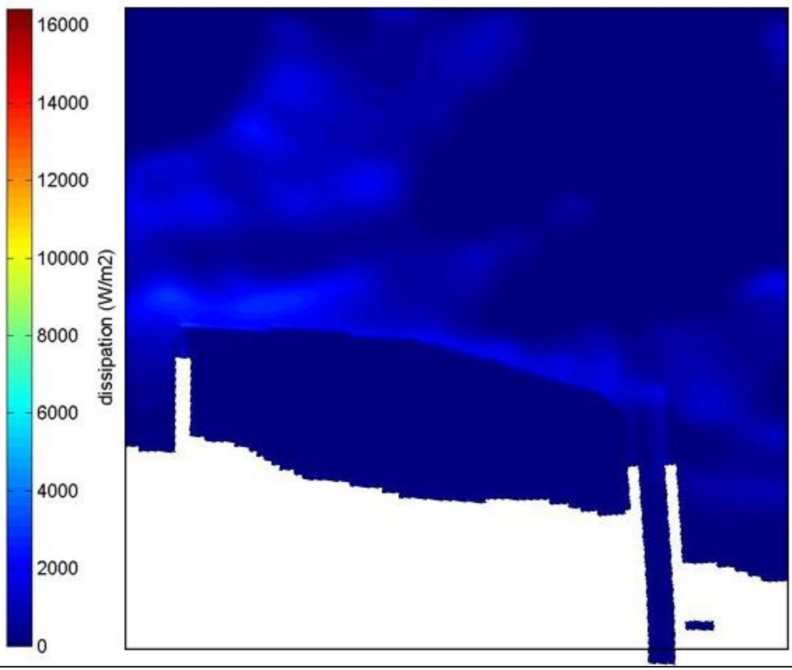
Bathymetry type:

- Nourished bathymetry

Present Structures:

- Extended Paso Malo groyne
- Extended western groyne
- Submerged breakwater

Wave dissipation figure:



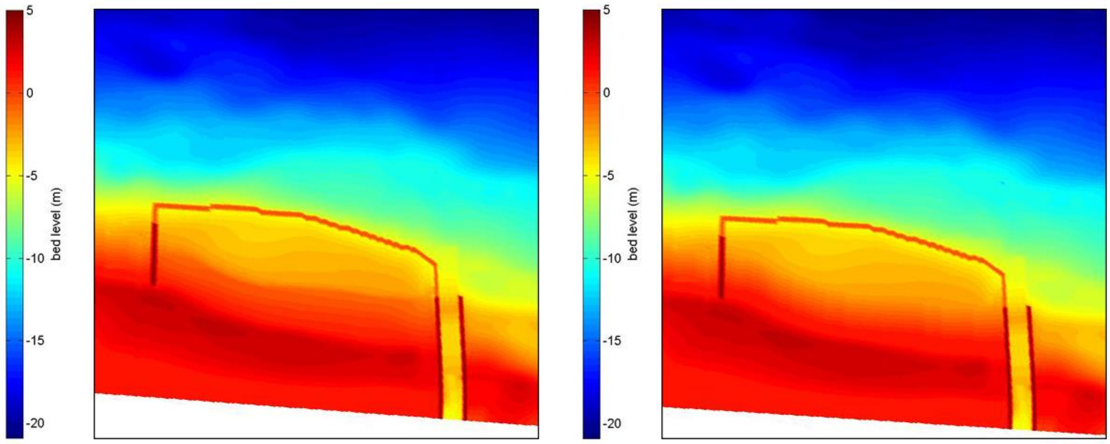
Key parameters (time-varying):
0.514 > H_s > 9.34 m
4.32 > T_p > 22.0 s
285° < β < 322° (nautical)

Computational key parameter:
morfac = 10
hmin 1.0
eps 0.05

Input files:
BathymetryM7813.dep
filelistIRMA.txt
jonswapI48-120.txt (73 files)
ne_layer_M78910.dep
TideIlong.txt
XBeachgrid510.grd

Errors/Cut-offs: As the first model indicated excessive flow over the Paso Malo groyne, the groyne was altered as if it was 5.0 m above water level. This made the model stable, and as the groyne is impermeable and overflow does not occur (though significant overtopping does), this is not expected to alter the model outcome significantly. To reduce the high flow velocity errors near the breakwater, hmin and eps parameters were included, to stop the model from calculating stokes drift and other flow effects in error-prone shallow zones.

Bed levels before and after simulation:



	Observations	Discussion
1.	Efficient energy dissipation at breakwater	During the entire storm, the breakwater dissipates the largest part of the wave energy. Especially during the most intense wave conditions the energy dissipation is significant.
2.	Little alongshore transport	The breakwater significantly reduces the overall transport and seems to reduce alongshore transport to near zero. The remaining transport is mostly cross-shore transport from the lower dunes to the foreshore.
3.	Limited profile change	Where the unprotected nourished profile would erode completely during hurricane Irma, the breakwater limits local bed level changes to less than 1.0 metres (accretion or erosion). The sediment is moved from the dry shore and lower dune are to the foreshore.

Model Number: 9.1 A

Model Title: Full protective measures in hurricane Irma morfac=5

Conditions modelled: Hurricane Irma

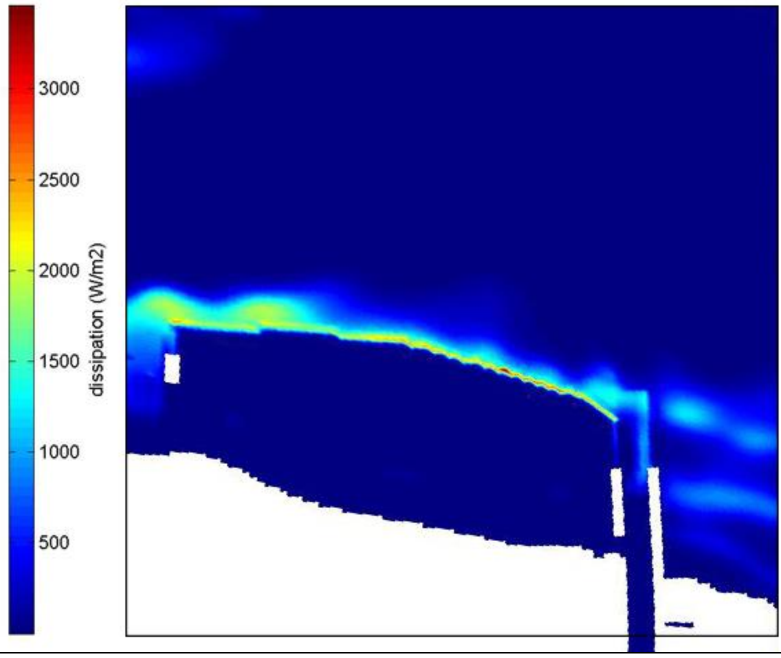
Bathymetry type:

- Nourished bathymetry

Present Structures:

- Extended Paso Malo groyne
- Extended western groyne
- Submerged breakwater

Wave dissipation figure:



Key parameters (time-varying):

0.514 > H_s > 9.34 m

4.32 > T_p > 22.0 s

285° < β < 322° (nautical)

Computational key parameter:

morfac = 10

hmin 1.0

eps 0.05

Input files:

BathymetryM91014.dep

filelistIRMA.txt

cf_coral.dep

jonswapI48-120.txt (73 files)

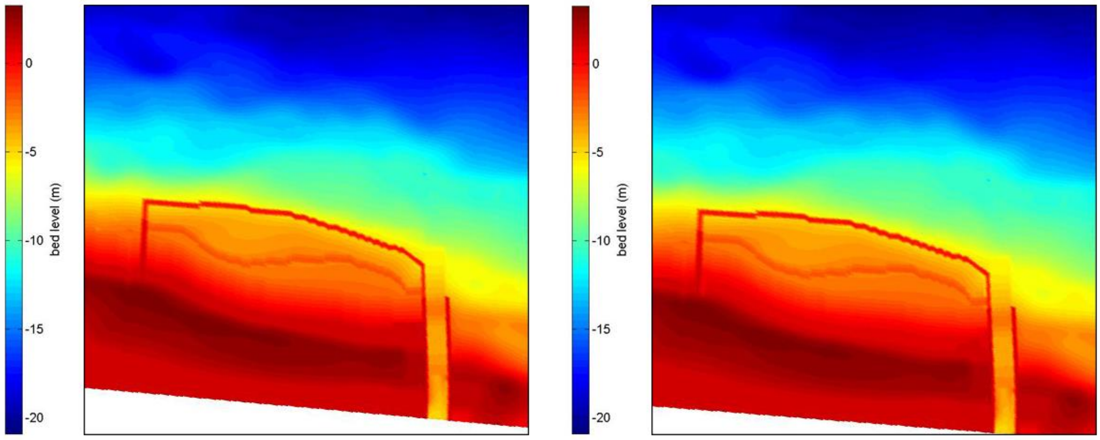
ne_layer_M78910.dep

TideIlong.txt

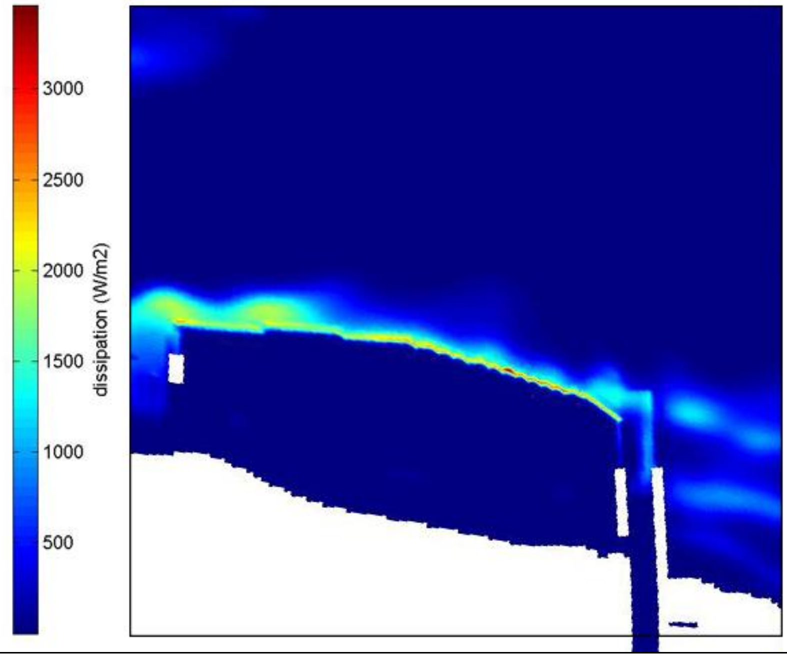
XBeachgrid510.grd

Errors/Cut-offs: As the first model indicated excessive flow over the Paso Malo groyne, the groyne was altered as if it was 5.0 m above water level. This made the model stable, and as the groyne is impermeable and overflow does not occur (though significant overtopping does), this is not expected to alter the model outcome significantly. To reduce the high flow velocity errors near the breakwater, hmin and eps parameters were included, to stop the model from calculating stokes drift and other flow effects in error-prone shallow zones.

Bed levels before and after simulation:



	Observations	Discussion
1.	The beach survives the entire storm	The model completes the simulation, sediment transport is clearly observed, but the solution does not fail as a flood protection system.
2.	Cross-shore transport	The transport by Irma is mostly cross-shore but is limited thanks to the extensive protective measures. The beach sediment does not reach the 4.0-metre depth contour, where the coral reef is placed. This makes the sediment easily retrievable by a corrective maintenance nourishment.
3.	Coral reef serves as friction energy dissipater	The presence of the closed breakwater causes large dissipation due to breaking, initiating breaking before the waves reach the reef. The reef then still dissipates wave energy but does this mostly through friction. The absolute effect of the coral reef is much smaller as compared to the reef being used as a separate solution.
4.	Effect morfac factor (morphological acceleration)	This model is used as a validation of the impact of varying morphological acceleration (morfac) factor. The discussion of this effect is found in the discussion of model 9b, observation 4.

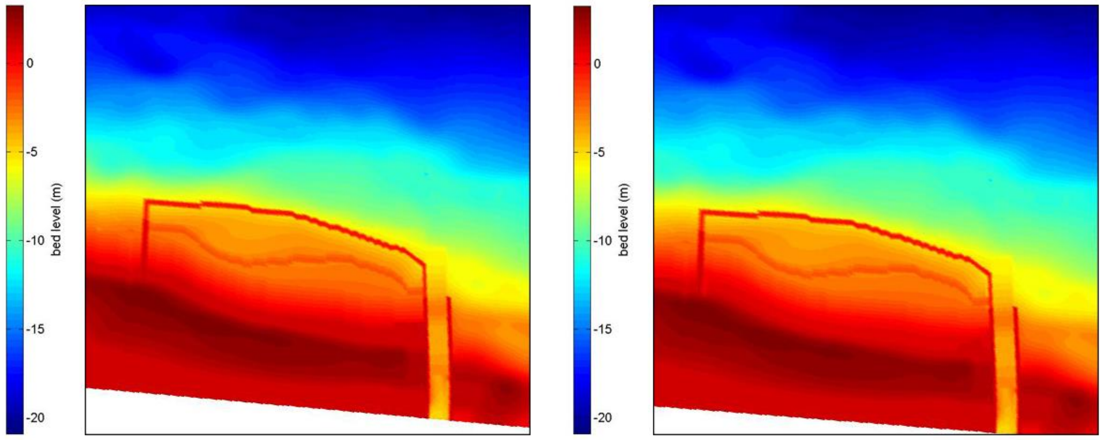
Model Number: 9.1 B	
Model Title: Full protective measures in hurricane Irma morfac=10	
Conditions modelled: Hurricane Irma	
Bathymetry type: **Present Structures:**	**Wave dissipation figure**: 

Key parameters (time-varying):
0.514 > H_s > 9.34 m
4.32 > T_p > 22.0 s
285° < β < 322° (nautical)
Computational key parameter:
morfac = 10

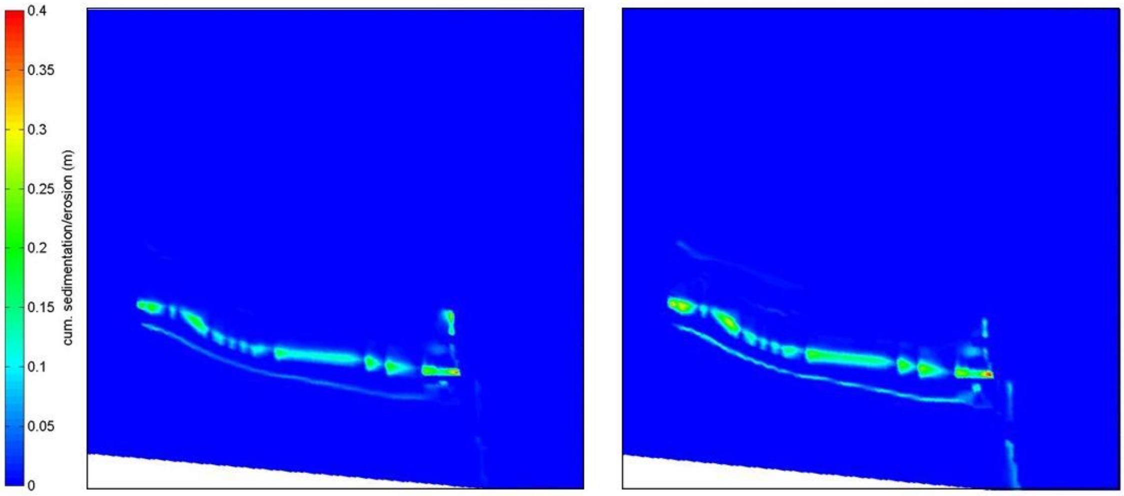
Input files:
BathymetryM91014.dep
cf_coral.dep
filelistIRMA.txt
jonswapI48-120.txt (73 files)
ne_layer_M78910.dep
TideIlong.txt
XBeachgrid510.grd

Errors/Cut-offs:
As the first model indicated excessive flow over the Paso Malo groyne, the groyne was altered as if it was 5.0 m above water level. This made the model stable, and as the groyne is impermeable and overflow does not occur (though significant overtopping does), this is not expected to alter the model outcome significantly.

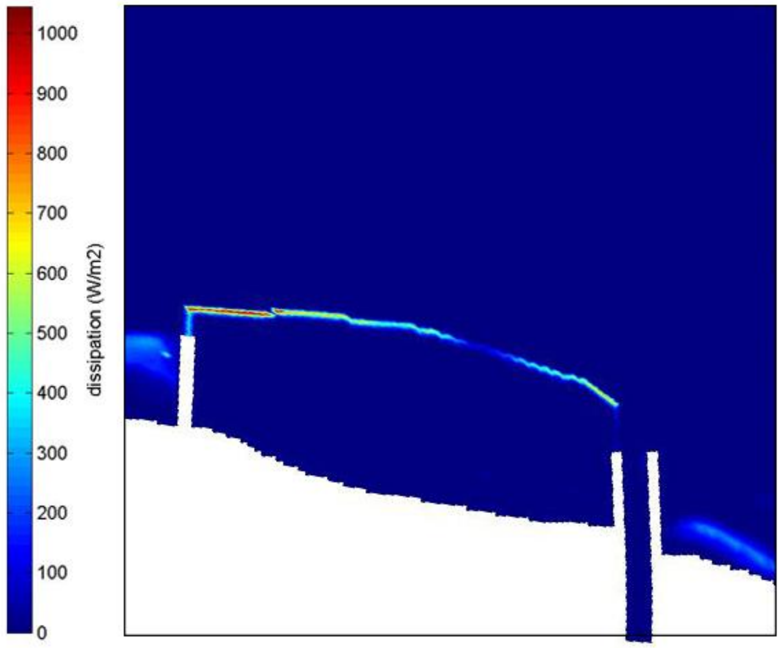
Bed levels before and after simulation:



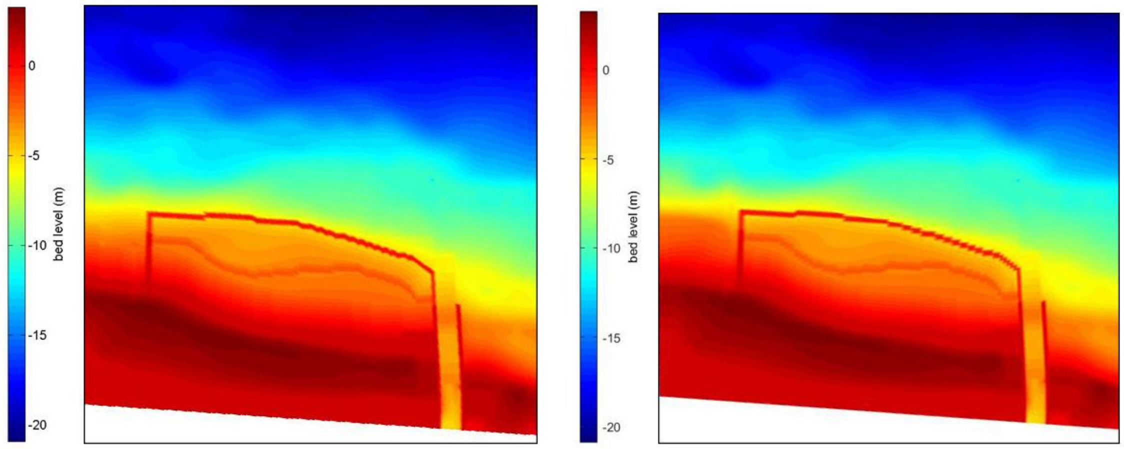
	Observations	Discussion
1.	The beach survives the entire storm	The model completes the simulation, sediment transport is clearly observed, but the solution does not fail as a flood protection system.
2.	Cross-shore transport	The transport by Irma is mostly cross-shore but is limited thanks to the extensive protective measures. The beach sediment does not reach the 4.0-metre depth contour, where the coral reef is placed. This makes the sediment easily retrievable by a corrective maintenance nourishment.
3.	Coral reef serves as friction energy dissipater	The presence of the closed breakwater causes large dissipation due to breaking, initiating breaking before the waves reach the reef. The reef then still dissipates wave energy but does this mostly through friction. The absolute effect of the coral reef is much smaller as compared to the reef being used as a separate solution.
4.	Effect morfac factor (morphological acceleration)	The comparison between a morphological acceleration factor of 5 (as used in model 9a) and a morfac of 10 (this model) is shown in the visualisation below. The left picture was made using a factor of 5, as used in model 9a, whereas the right picture shows the cumulative sedimentation/erosion pattern using a morfac of 10 (model 9b). It becomes clear that the use of a higher morfac slightly overestimates the sedimentation and erosion.

	Visualisations for discussion
4.	

<table>
<tr><td colspan="2">Model Number: 10.3</td></tr>
<tr><td colspan="2">Model Title:</td></tr>
<tr><td colspan="2">Conditions modelled: Cold front conditions</td></tr>
<tr><td>Bathymetry type:
• Nourished bathymetry, coral

Present Structures:
• Extended Paso Malo groyne
• Extended western groyne
• Submerged breakwater</td><td>Wave dissipation figure:

</td></tr>
<tr><td colspan="2">Key parameters: $H_s = 2.10$ $T_p = 4.67$ $\beta = 315°$ (nautical)</td></tr>
<tr><td colspan="2">Input files:
BathymetryM91014.dep
cf_coral.dep
filelistIRMA.txt
jonswapI48-120.txt (73 files)
ne_layer_M78910.dep
TideIlong.txt
XBeachgrid510.grd</td></tr>
<tr><td colspan="2">Errors/Cut-offs: As the first model indicated excessive flow over the Paso Malo groyne, the groyne was altered as if it was 5.0 m above water level. This made the model stable, and as the groyne is impermeable and overflow does not occur (though significant overtopping does), this is not expected to alter the model outcome significantly. To reduce the high flow velocity errors near the breakwater, hmin and eps parameters were included, to stop the model from calculating stokes drift and other flow effects in error-prone shallow zones.</td></tr>
</table>

Bed levels before and after simulation:



	Observations	Discussion
1.	Near zero alongshore transport	The eastward longshore sediment transport is near zero, which shows from the final sedimentation (see visualisation). There is no clear difference between erosion and accretion between the west and east side of the Oasis sector.
2.	Remarkable sedimentation/erosion pattern	The varying alongshore sedimentation/erosion pattern as observed in model 5 is somewhat less clear, but still present here. It seems the wave energy dissipation varies somewhat for the location alongshore.
3.	Total sedimentation/erosion	The breakwater and extended groynes result in a maximum erosion of approximately -0.1 metres in the west end of the Oasis beach but result in an accumulation of 0.5 metres near the Paso Malo groyne (which is a small local cross shore transport).
4.	Wave dissipation mostly on breakwater	The wave dissipation is caused mostly by the breakwater; however, the coral reef continuously dissipates the remainder of the wave energy, leaving little to no wave energy to reach the shoreline.

Model Number: 11.2

Model Title: Zero-reference Hurricane Wilma

Conditions modelled: Hurricane Wilma

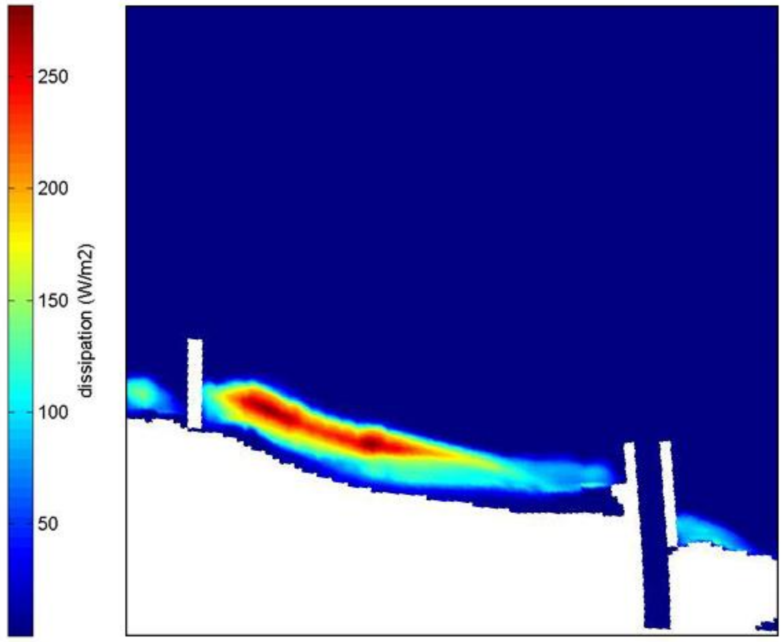
Bathymetry type:

- Nourished bathymetry

Present Structures:

- Paso Malo groyne
- Western groyne

Wave dissipation figure:



Key parameters (time-varying):

$0.51 < H_s < 7.31$ m

$4.32 < T_p < 21.5$ s

$285 < \beta < 75°$ (nautical)

Input files:

BathymetryM910.dep

cf_coral.dep

filelistW.txt

jonswapI61-120.txt (73 files)

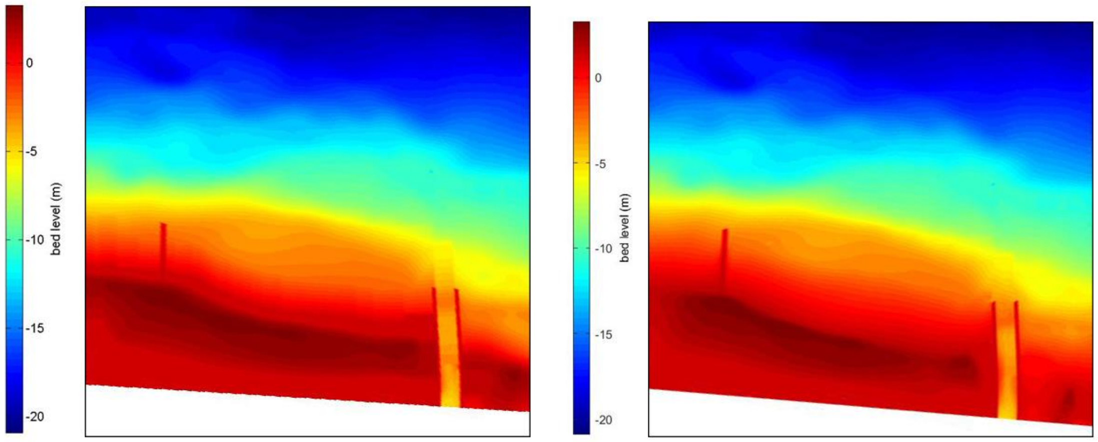
TideIlong.txt

XBeachgrid510.grd

Errors/Cut-offs:

As the first model indicated excessive flow over the Paso Malo groyne, the groyne was altered as if it was 5.0 m above water level. This made the model stable, and as the groyne is impermeable and overflow does not occur (though significant overtopping does), this is not expected to alter the model outcome significantly.

Bed levels before and after simulation:



	Observations	Discussion
1.	Model cuts off before the peak intensity is reached	The wave height of hurricane Wilma is less than that of hurricane Irma (model 3.2), however, the wave angle of incidence is much closer to shore-normal, resulting in larger erosion of the Oasis beach.
2.	Sediment enters Paso Malo	Significant volumes of sediment are deposited in the Paso Malo entrance, as well as further into the channel. The additional sediment layer has a thickness of approximately 1.0 metre, reaching a maximum of 1.9 metres locally.
3.	Small area of dissipation	Due to the steep, narrow foreshore, wave energy is not gradually dissipated. Erosion therefore occurs in a very small band nearshore and progresses quickly.

Model Number: 12.2

Model Title: Reef exposure to distant hurricane

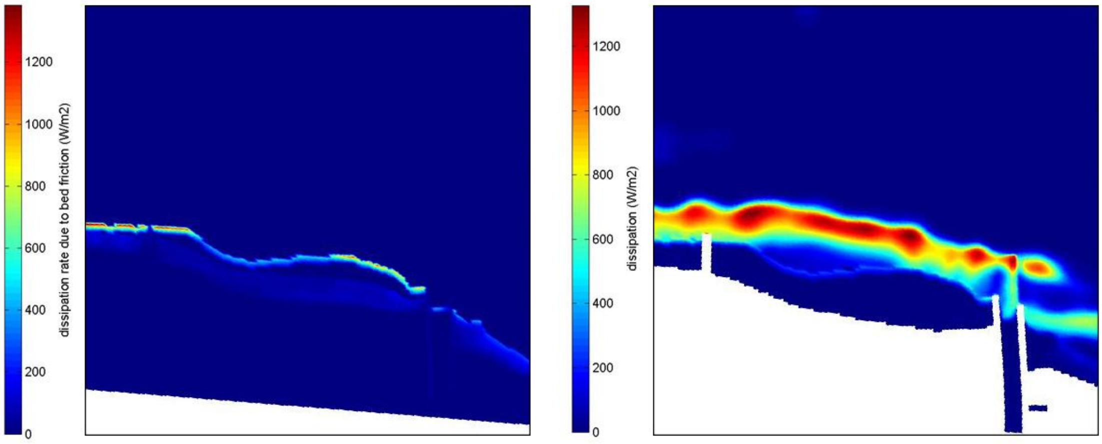
Conditions modelled: Hurricane Wilma

Bathymetry type:
Nourished bathymetry, coral

Present Structures:

- Paso Malo groyne
- Western groyne

Wave dissipation and bed friction dissipation:



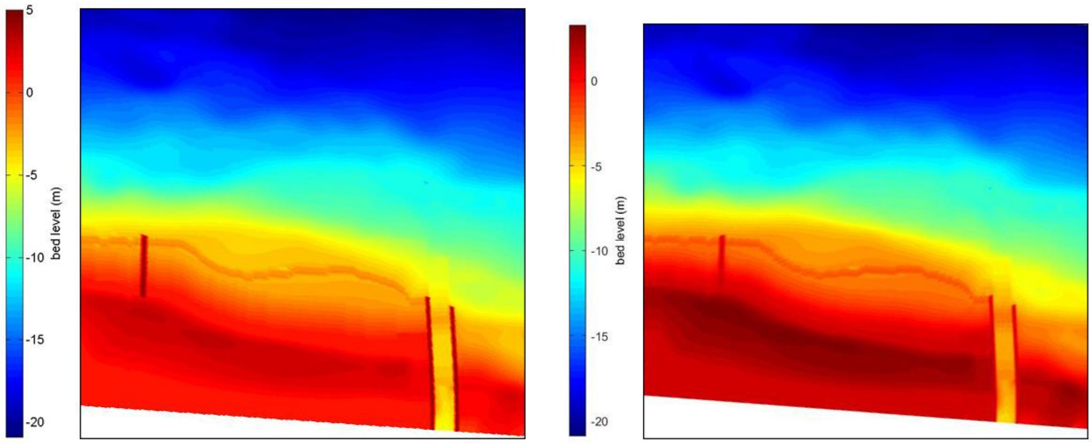
Key parameters (time-varying):
0.51 < H_s < 7.31 m
4.32 < T_p <21.5 s
285 < β < 75° (nautical)

Computational key parameter:
morfac = 10
hmin 1.0
eps 0.05

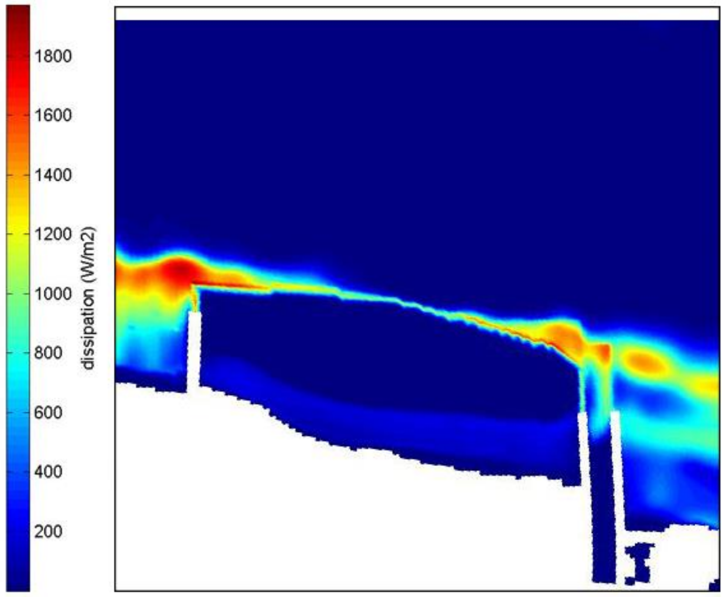
Input files:
bathymetryM45612.dep
cf_coral.dep
filelistW.txt
jonswapW61-120.txt (60 files)
TideW.txt
XBeachgrid510.grd

Errors/Cut-offs: As the first model indicated excessive flow over the Paso Malo groyne, the groyne was altered as if it was 5.0 m above water level. This made the model stable, and as the groyne is impermeable and overflow does not occur (though significant overtopping does), this is not expected to alter the model outcome significantly. To reduce the high flow errors near the breakwater, hmin and eps parameters were included, to stop the model from calculating stokes drift and other flow effects in error-prone shallow zones.

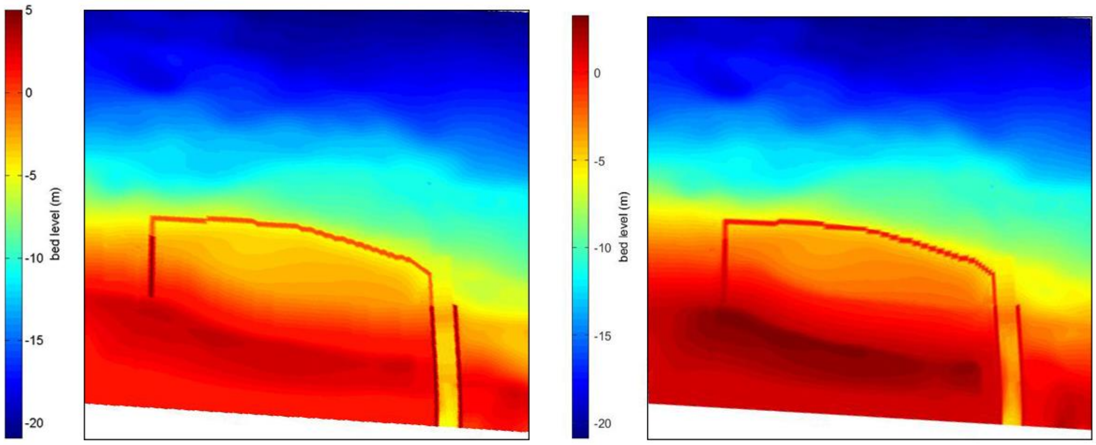
Bed levels before and after simulation:



	Observations	Discussion
1.	Dissipation occurs mostly before the coral reef	Due to the extremely large wave heights hurricane Wilma produces, the waves start to dissipate in deep water, causing dissipation before the wave even reaches the reef.
2.	Erosion of the dry beach	The dry beach is eroded significantly (up to 0.5 metres). The sediment is deposited between the initial shoreline and the location of the coral reef (the three-metre depth contour).
3.	Erosion near western groyne	The beach erodes over a much longer cross-shore area near the western groyne. This sediment is transported alongshore to the middle of the Oasis section.

Model Number: 13.2	
Model Title: Full hard structures in extreme conditions	
Conditions modelled: Hurricane Wilma	
Bathymetry type: • Nourished bathymetry **Present Structures:** • Extended Paso Malo groyne • Extended western groyne • Submerged breakwater	**Wave dissipation figure**: 
Key parameters (time-varying): $0.51 < H_s < 7.31$ m $4.32 < T_p < 21.5$ s $285 < \beta < 75°$ (nautical) **Computational key parameter:** morfac = 10 hmin 1.0 eps 0.05	
Input files: BathymetryM7813.dep filelistW.txt jonswapW61-120.txt (60 files) ne_layer_M78910.dep tideW.txt XBeachgrid510.grd	
Errors/Cut-offs: As the first model indicated excessive flow over the Paso Malo groyne, the groyne was altered as if it was 5.0 m above water level. This made the model stable, and as the groyne is impermeable and overflow does not occur (though significant overtopping does), this is not expected to alter the model outcome significantly. To reduce the high flow velocity errors near the breakwater, hmin and eps parameters were included, to stop the model from calculating stokes drift and other flow effects in error-prone shallow zones.	

Bed levels before and after simulation:



	Observations	Discussion
1.	Dissipation occurs mostly before the coral reef	Due to the extremely large wave heights hurricane Wilma produces, the waves start to dissipate in deep water, causing dissipation before the wave even reaches the reef.
2.	Erosion of the dry beach	The dry beach is eroded significantly (up to 0.5 metres). The sediment is deposited between the initial shoreline and the location of the coral reef (the three-metre depth contour).
3.	Erosion near western groyne	The beach erodes over a much longer cross-shore area near the western groyne. This sediment is transported alongshore to the middle of the Oasis section.

Model Number: 14.2

Model Title: Full protective measures in hurricane Wilma

Conditions modelled: Hurricane Wilma

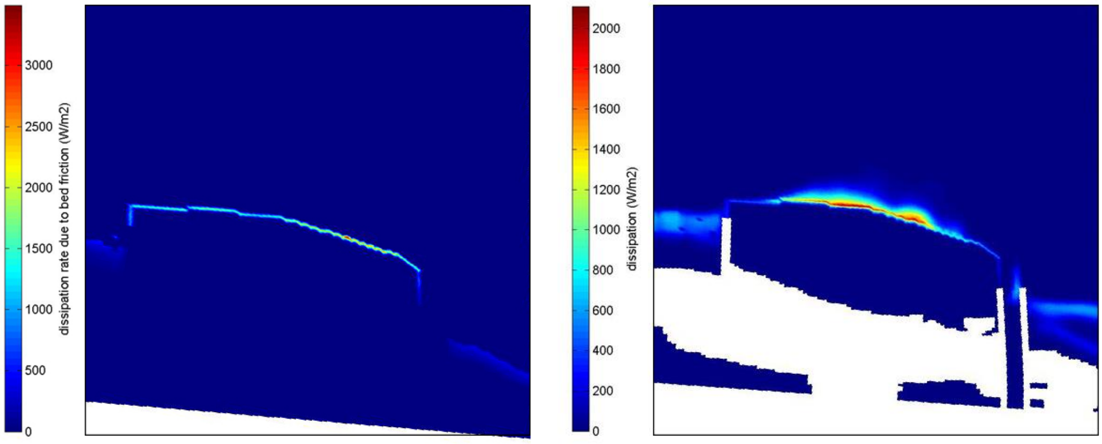
Bathymetry type:

- Nourished bathymetry, coral

Present Structures:

- Extended Paso Malo groyne
- Extended western groyne
- Submerged breakwater

Wave dissipation and bed friction dissipation:



Key parameters (time-varying):

$0.51 < H_s < 7.31$ m

$4.32 < T_p < 21.5$ s

$285 < \beta < 75°$ (nautical)

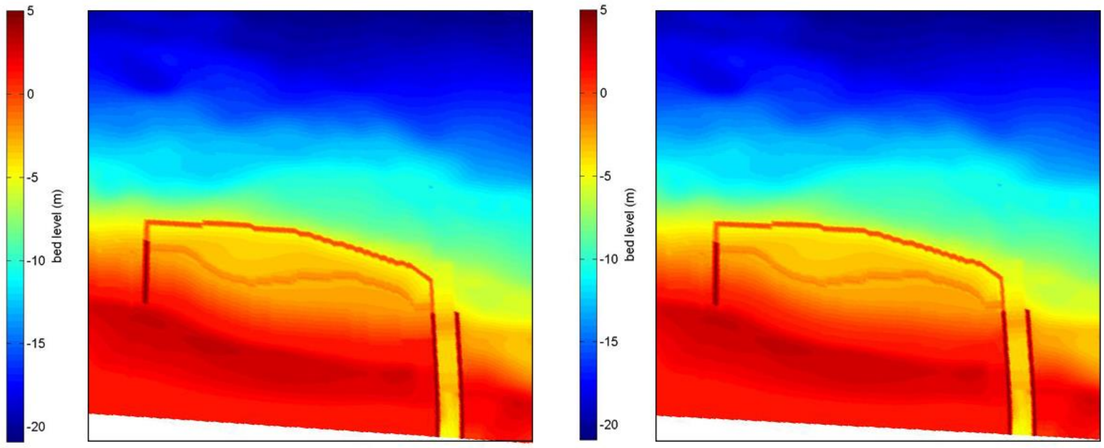
Input files:

BathymetryM91014.dep
cf_coral.dep
ne_layer_M8910.dep
tideWlong.txt
filelistW.txt
jonswapW61-120 (60 files)
XBeachgrid510.grd

Errors/Cut-offs:

As the first model indicated excessive flow over the Paso Malo groyne, the groyne was altered as if it was 5.0 m above water level. This made the model stable, and as the groyne is impermeable and overflow does not occur (though significant overtopping does), this is not expected to alter the model outcome significantly.

Bed levels before and after simulation:



	Observations	Discussion
1.	Most complete wave dissipation	The wave breaker dissipates most of the wave energy. The influence of the coral reef on wave dissipation is very small. Combined, this results in the best wave dissipation observed.
2.	Smallest erosion observed in these conditions	Various local erosion spots show bed degradation up to 0.8 metre. Along the beach, erosion averages approximately 0.2 metres and sediment is deposited in the shallow submerged zone, where depth does not exceed 3.0 metres. The sediment therefore is easily retrieved.
3.	Effect of coral reef smaller than as separate option	The combination of the breakwater and coral reef functions very well, however, the effect of the breakwater and coral reef is not simply summed up. As the breakwater induces wave breaking, the effect of the coral reef is reduced as compared to only applying the coral reef.

Model Number: 15.0

Model Title: Full hard measures in normal conditions

Conditions modelled: Normal conditions

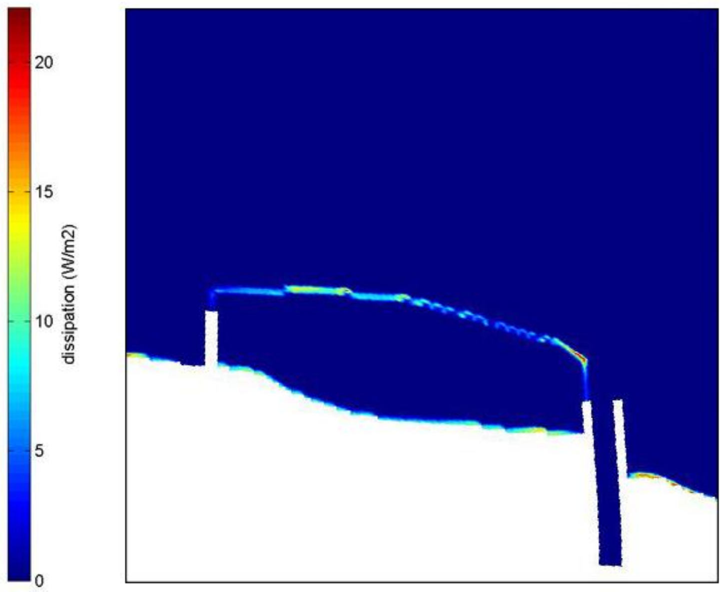
Bathymetry type:

- Nourished bathymetry, no coral

Present Structures:

- Extended Paso Malo groyne
- Extended western groyne
- Submerged breakwater

Wave dissipation



Key parameters (time-varying):

$H_s = 0.52$ m

$T_p = 4.32$ s

$\beta < 68°$ (nautical)

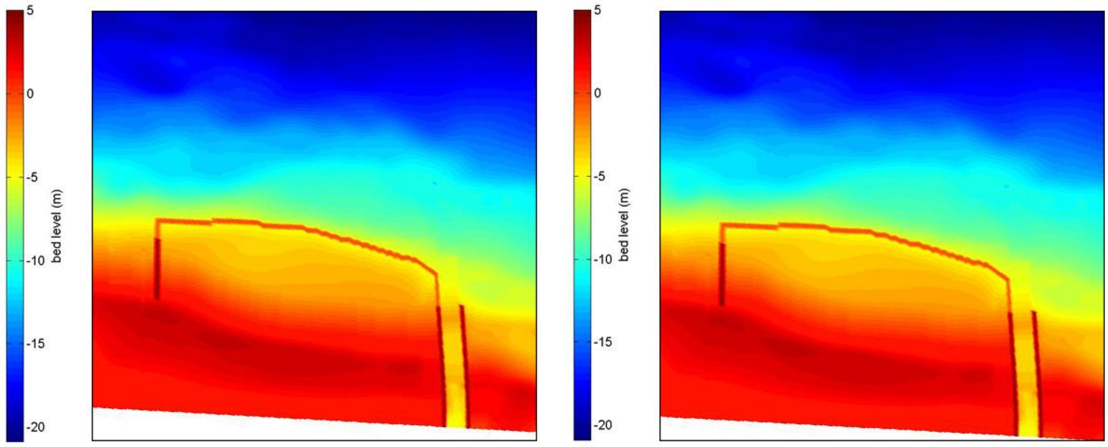
Input files:

BathymetryM7813.dep
ne_layer_M78910.dep
tidenorMalong.txt
jonswapN.txt
XBeachgrid510.grd

Errors/Cut-offs:

To prevent cut-offs, the parameter *eps* has been lowered and *hmin* has been increased. This prevents high flow speeds above hard structures by excluding a part of the flow computations (stokes drift) and only regards cells as wet when the depth is relatively high, preventing errors from occurring.

Bed levels before and after simulation:



	Observations	Discussion
1.	Minimal erosion	As the model only runs for a simulated 5 days, little sedimentation or erosion is observed. However, on 349 days per year these conditions are present. Therefore, the results will likely be more significant when the transport is extrapolated to the lifetime period in result analysis.
2.	Breakwater functions for small waves	Even for these smaller waves, the breakwater causes a significant reduction of energy dissipation at the dry shore, which is likely to result in reduced sediment transport.
3.	Minimal bed level changes	The bed level changes observed are local and small. The general bed level change throughout the profile is not even a centimetre.

Model Number: 16.0

Model Title: Full protective measures in normal conditions

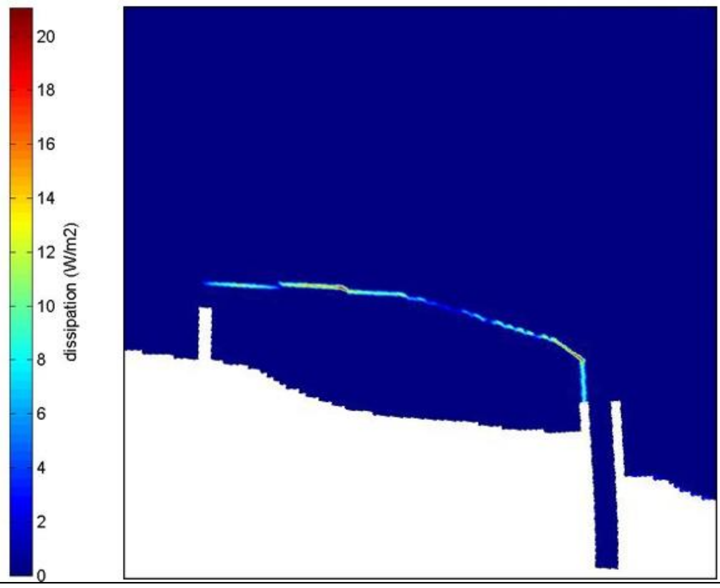
Conditions modelled: Normal conditions

Bathymetry type:

- Nourished bathymetry
- Coral reef

Present Structures:

- Extended Paso Malo groyne
- Extended western groyne
- Submerged breakwater



Key parameters (time-varying):

$H_s = 0.52$ m

$T_p = 4.32$ s

$\beta < 68°$ (nautical)

Input files:

BathymetryM7813.dep

ne_layer_M78910.dep

tidenorMalong.txt

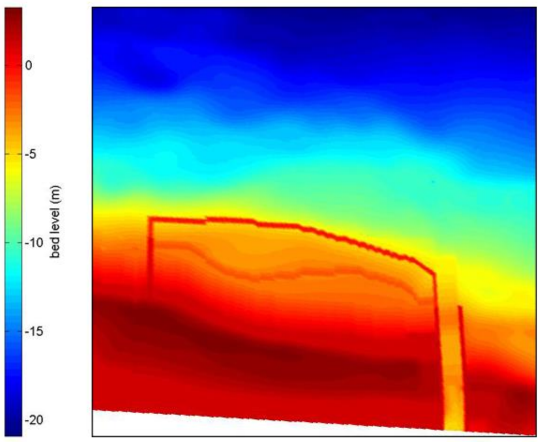
jonswapN.txt

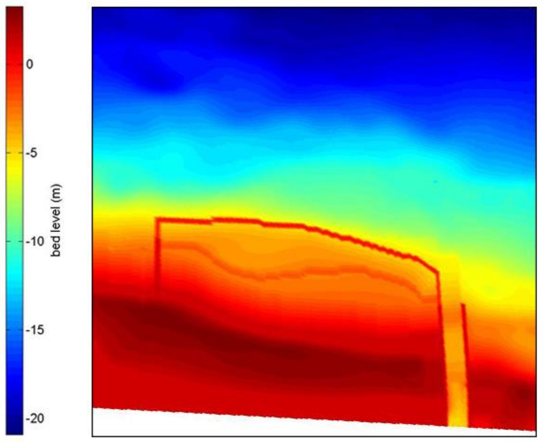
XBeachgrid510.grd

Errors/Cut-offs:

To prevent cut-offs, the parameter *eps* has been lowered and *hmin* has been increased. This prevents high flow speeds above hard structures by excluding a part of the flow computations (stokes drift) and only regards cells as wet when the depth is relatively high, preventing errors from occurring.

Bed levels before and after simulation:





	Observations	Discussion
1.	Minimal erosion	As the model only runs for a simulated 5 days, little sedimentation or erosion is observed. However, on 349 days per year these conditions are present. Therefore, the results will likely be more significant when the transport is extrapolated to the lifetime period in result analysis.
2.	Coral reef dissipates no wave energy	The coral reef does not dissipate wave energy in these normal (low-energy) wave conditions. This was to be expected, as coral reef dissipation increases nonlinear with wave height. This also shows that the coral reef can grow in normal conditions, as the loads on the coral are small, but the water is still constantly in motion.
3.	Breakwater functions for small waves	Even for these smaller waves, the breakwater causes a significant reduction of energy dissipation at the dry shore, which is likely to result in reduced sediment transport.
4.	Minimal bed level changes	The bed level changes observed are local and small. The general bed level change throughout the profile is not even a centimetre.

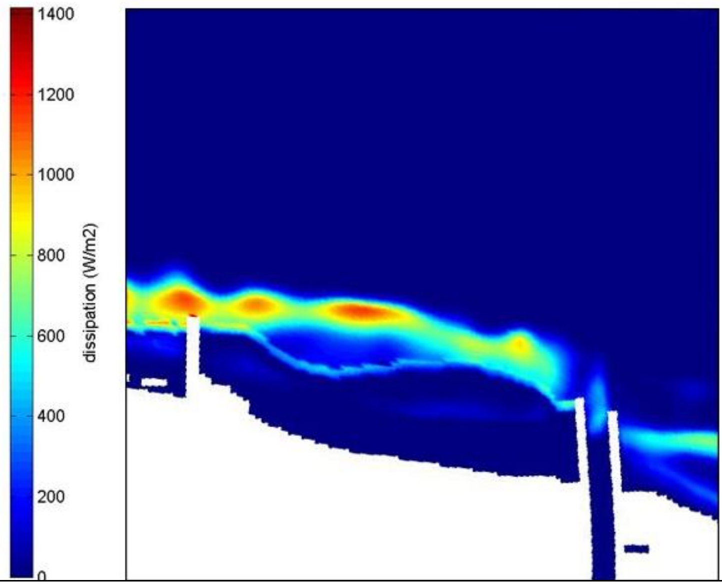
Model Number:	DO 1.0
Model Title:	Coral reef in hurricane Wilma including vegetation
Conditions modelled:	Hurricane Wilma conditions

Bathymetry type:

- Nourished bathymetry
- Coral reef
- Dune vegetation

Present Structures:

- Paso Malo groyne
- Western groyne



Key parameters (time-varying):

$0.51 < H_s < 7.31$ m

$4.32 < T_p < 21.5$ s

$285 < \beta < 75°$ (nautical)

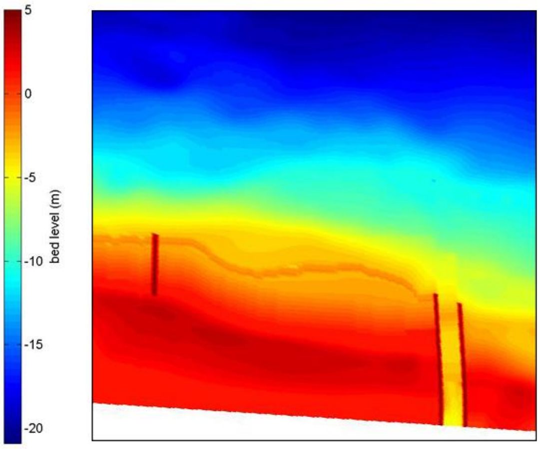
Input files:

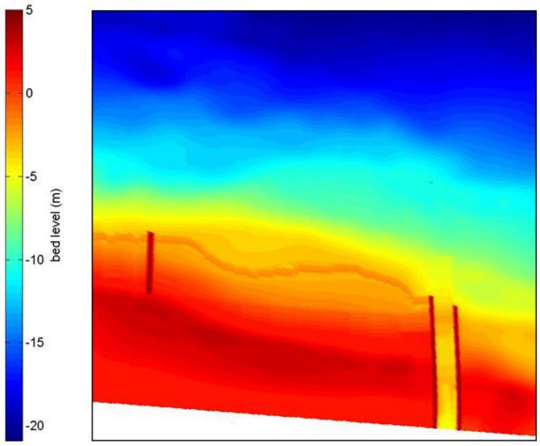
BathymetryM45612.dep
cf_coral.dep
ne_layerM456.dep
veggiefile.txt
veggiemap.dep
treebushes.txt
grassmoss.txt
filelistW.txt
jonswapI61-120.txt (73 files)
TideW.txt
XBeachgrid510.grd

Errors/Cut-offs:

To prevent cut-offs, the parameter *eps* has been lowered and *hmin* has been increased. This prevents high flow speeds above hard structures by excluding a part of the flow computations (stokes drift) and only regards cells as wet when the depth is relatively high, preventing errors from occurring.

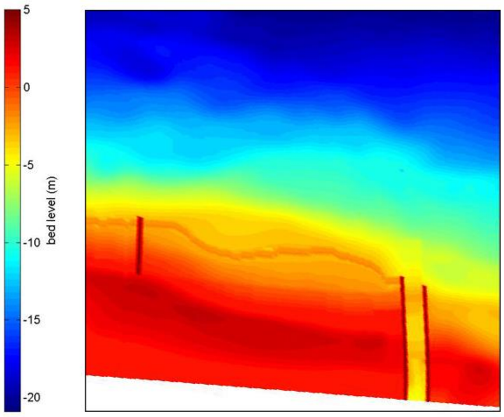
Bed levels before and after simulation:

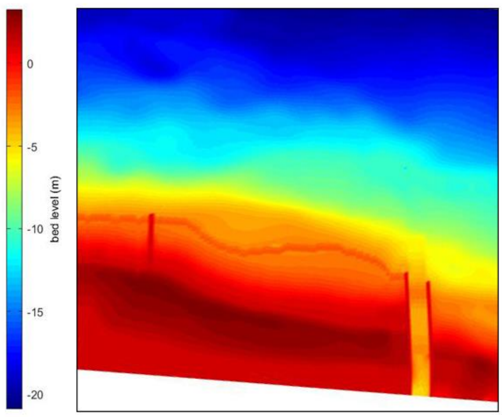




	Observations	Discussion
1.	Vegetation has a significant influence on dune stability	Compared to model 12, in which this same simulation was made, without the influence of dune vegetation, significant sediment transport was observed. The comparison is shown in the visualisation. The sediment transport will be calculated to determine the required nourishment interval for the definitive design. This is shown in the beach profile after hurricane Wilma for both situations. Note that the profile for unvegetated dunes (left) shows a more gradual bed level decline to the breakwater, indicating offshore transport of the dunes.

	Visualisations for discussion
1.	Comparison: bathymetries after modelling without dune vegetation (left, model DO1) and with vegetation (right, model 12)





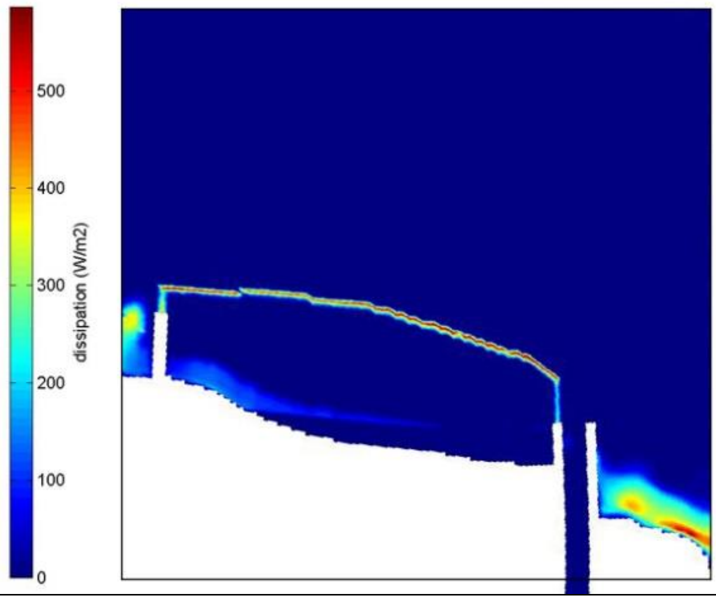
Model Number:	DO 2.0
Model Title:	Breakwater in hurricane Wilma including vegetation
Conditions modelled:	Hurricane Wilma conditions

Bathymetry type:

- Nourished bathymetry
- Dune vegetation

Present Structures:

- Extended Paso Malo groyne
- Extended western groyne

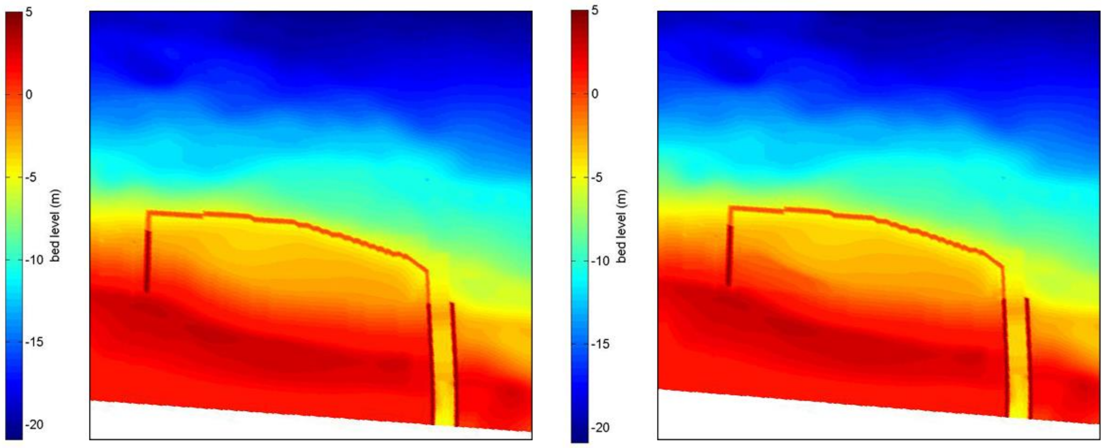


Key parameters (time-varying):
$0.51 < H_s < 7.31$ m
$4.32 < T_p < 21.5$ s
$285 < \beta < 75°$ (nautical)

Input files:
BathymetryM7813.dep
ne_layerM78910.dep
veggiefile.txt
veggiemap.dep
treebushes.txt
grassmoss.txt
filelistW.txt
jonswapI61-120.txt (73 files)
TideW.txt
XBeachgrid510.grd

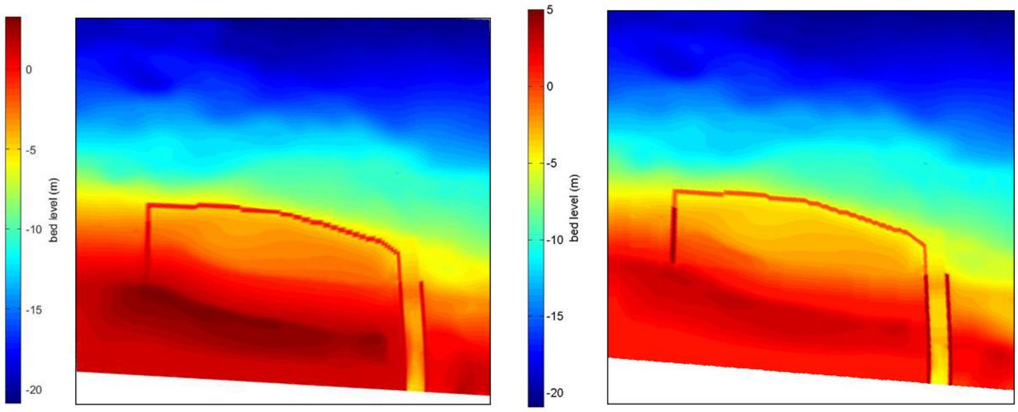
Errors/Cut-offs:
To prevent cut-offs, the parameter *eps* has been lowered and *hmin* has been increased. This prevents high flow speeds above hard structures by excluding a part of the flow computations (stokes drift) and only regards cells as wet when the depth is relatively high, preventing errors from occurring.

Bed levels before and after simulation:



	Observations	Discussion
1.	Vegetation has a significant influence on dune stability	Compared to model 13, in which this same simulation was made, without the influence of dune vegetation, significant sediment transport was observed. The comparison is shown in the visualisation. The sediment transport will be calculated to determine the required nourishment interval for the definitive design. This is shown in the beach profile after hurricane Wilma for both situations. Note that the profile for unvegetated dunes (left) shows a more gradual bed level decline to the breakwater, indicating offshore transport of the dunes.

	Visualisations for discussion
1.	Comparison: bathymetries after modelling without dune vegetation (left, model 13) and with vegetation (right, model DO2)



Model Number: DO 3.0

Model Title: Full protective measures in hurricane Wilma including vegetation

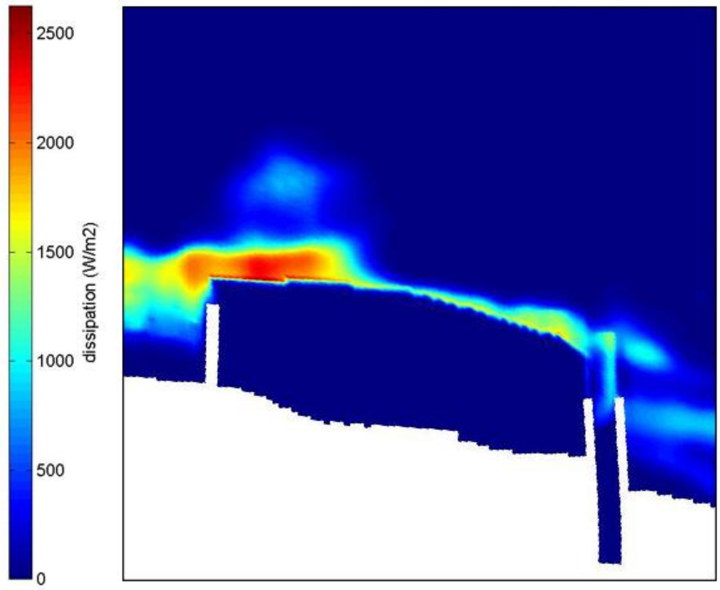
Conditions modelled: Normal conditions

Bathymetry type:

- Nourished bathymetry
- Coral reef
- Dune vegetation

Present Structures:

- Extended Paso Malo groyne
- Extended western groyne
- Submerged breakwater



Key parameters (time-varying):

$0.51 < H_s < 7.31$ m

$4.32 < T_p < 21.5$ s

$285 < \beta < 75°$ (nautical)

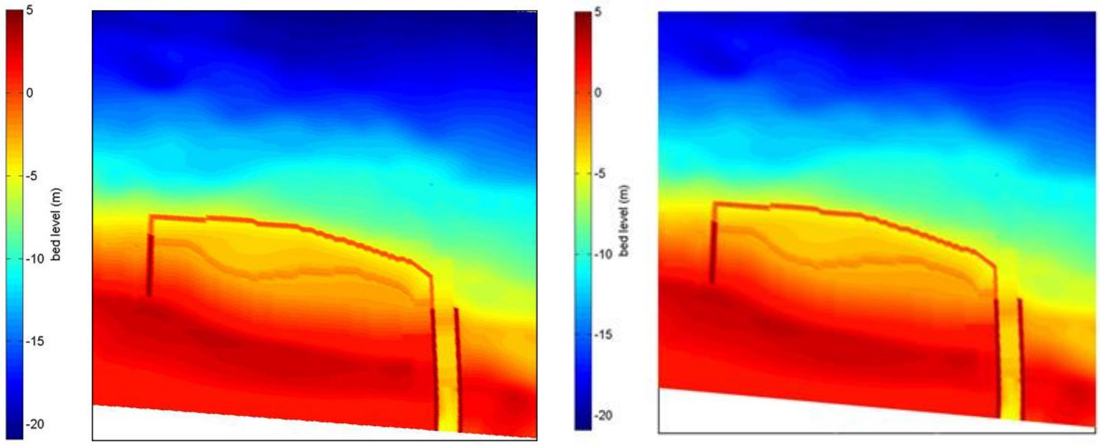
Input files:

BathymetryM91014.dep
ne_layerM78910.dep
cf_coral.dep
veggiefile.txt
veggiemap.dep
treebushes.txt
grassmoss.txt
filelistW.txt
jonswapI61-120.txt (73 files)
TideW.txt
XBeachgrid510.grd

Errors/Cut-offs:

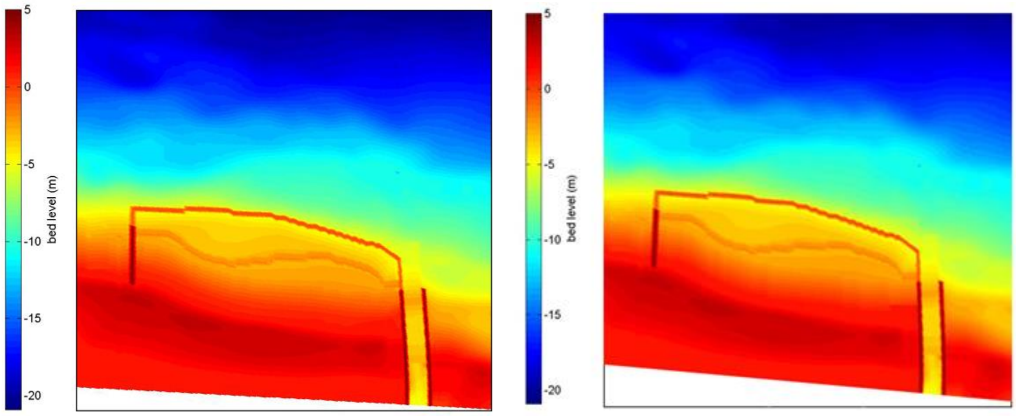
To prevent cut-offs, the parameter *eps* has been lowered and *hmin* has been increased. This prevents high flow speeds above hard structures by excluding a part of the flow computations (stokes drift) and only regards cells as wet when the depth is relatively high, preventing errors from occurring.

Bed levels before and after simulation:



	Observations	Discussion
1.	Vegetation has a significant influence on dune stability	Compared to model 14, in which this same simulation was made, without the influence of dune vegetation, significant sediment transport was observed. The comparison is shown in the visualisation. The sediment transport will be calculated to determine the required nourishment interval for the definitive design. This is shown in the beach profile after hurricane Wilma for both situations. Note that the profile for unvegetated dunes (left) shows a more gradual bed level decline to the breakwater, indicating offshore transport of the dunes.

	Visualisations for discussion
1.	Left: bathymetry after model run (no vegetation) – Right: Including vegetation



J. Simio simulation

J.1 Experiment current situation

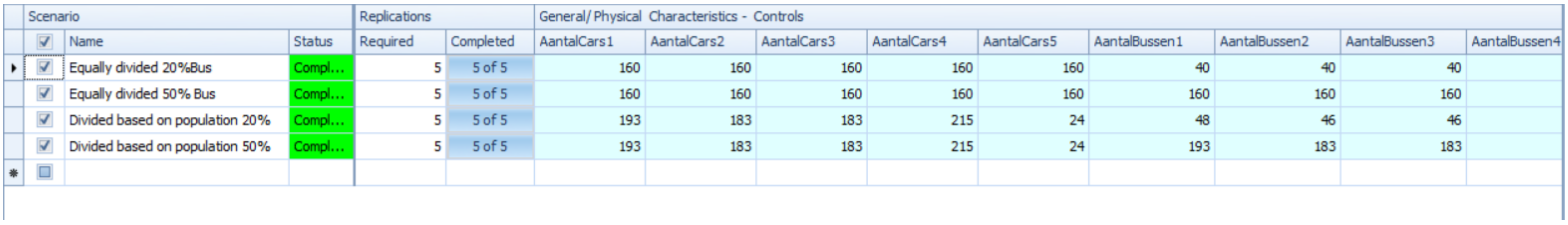
Table J.1 gives the distribution of the population over the five zones on the Hicacos peninsula. Table J.2 gives the distribution of vehicles and figure J.1 shows how this implemented in the experiment.

Table J.1. Distribution of population in current situation

Zone	Distribution	Distribution population	Transported by bus (60%)	Transported by car (40%)
1	11,953 tourists + 11,115 locals	24%	14,097	9,396
2	7,968 tourists + 14,650 locals	23%	13,434	8,956
3	7,968 tourists + 14,650 locals	23%	13,434	8,956
4	11,953 tourists + 15,253 locals	27%	16,171	10,781
5	2,069 locals	3%	1,385	923

Table J.2. Distribution of vehicles

Zone	Cars (798)	Buses 20% (200)	Buses 50% (798)	Distribution population	Cars (798)	Buses 20% (200)	Buses 50%(798)
1	160	40	160	24%	192	48	192
2	160	40	160	23%	183	46	183
3	160	40	160	23%	184	46	184
4	160	40	160	27%	215	54	215
5	160	40	160	3%	24	6	24



Scenario			Replications		General/ Physical Characteristics - Controls								
	Name	Status	Required	Completed	AantalCars1	AantalCars2	AantalCars3	AantalCars4	AantalCars5	AantalBussen1	AantalBussen2	AantalBussen3	AantalBussen4
☑	Equally divided 20%Bus	Compl...	5	5 of 5	160	160	160	160	160	40	40	40	
☑	Equally divided 50% Bus	Compl...	5	5 of 5	160	160	160	160	160	160	160	160	
☑	Divided based on population 20%	Compl...	5	5 of 5	193	183	183	215	24	48	46	46	
☑	Divided based on population 50%	Compl...	5	5 of 5	193	183	183	215	24	193	183	183	

Figure J.1. Experiment current situation

J.2 Scenarios

In the forecasted scenarios, the distribution of the population over the zones will change. The changes in distribution can be seen in table J.3.

Table J.3 Distribution of population in forecasted scenarios

Zone	Distribution of populations
1	40% of tourists + 30% local (30% employee)
2	15% of tourists + 21% local (11% inhabitant + 10% employee)
3	15% of tourists + 20% local (10% inhabitant + 10% employee)
4	30 % of tourists + 26% locals (6% inhabitant + 20% employee)
5	3 % local (inhabitants)

Scenario MinTur

Table J.4 gives the distribution of the population over the five zones on the Hicacos peninsula in scenario MinTur. Table J.5 gives the distribution of vehicles according to the conditions in the current situation.

Table J.4 Distribution of population

Zone	Distribution	Total population	Distribution population	Transported by bus	Transported by car
1	84,000 tourists + 20,462 locals	104,462	38%	62,677	41,785
2	31,500 tourists + 14,324 locals	45,824	16%	27,494	18,330
3	31,500 tourists + 13,642 locals	45,142	16%	27,085	18,057
4	63,000 tourists + 17,734 locals	80,734	29%	48,440	32,294
5	2,046 locals		1%	1,228	818

Table J.5. Distribution of vehicles

Zone	Distribution population	Cars (806)	Bus 20% (202)	Bus 50% (806)
1	38%	306	77	306
2	16%	129	32	129
3	16%	129	32	129
4	29%	234	59	234
5	1%	8	2	8

Table J6, J7 and J8 give different distributions of the population among the vehicles simulated in experiments to find the optimal distribution with the shortest evacuation time. Table J9 gives the results of these experiments.

Table J6. Distribution of population 70% by bus and 30% by car

Zone	Distribution population	Transported by bus	Transported by car
1	104,462	73,123	31,339
2	45,824	32,077	13,747
3	45,142	31,599	13,543
4	80,734	56,514	24,220
5	2,046	1,432	614

Table J7. Distribution of population 50% by bus and 50% by car

Zone	Distribution population	Transported by bus	Transported by car
1	104,462	52,231	52,231
2	45,824	22,912	22,912
3	45,142	22,571	22,571
4	80,734	40,367	40,367
5	2,046	1,023	1,023

Table J8. Distribution of population with 40% bus and 60% car

Zone	Distribution population	Transported by bus	Transported by car
1	104,462	41,785	62,677
2	45,824	18,330	27,494
3	45,142	18,057	27,085
4	80,734	32,294	48,440
5	2,046	818	1,228

Table J9. Results of the experiments with different distributions of the population among vehicles

	60% bus	70% bus	50% bus	40% bus
	Time [h]	Time [h]	Time [h]	Time [h]
Current number of vehicles 20% bus	26.96	31.14	25.98	31.11
Current number of vehicles 50% bus	26.96	31.09	25.97	31.10

Table J10 gives the number of vehicles with different increases in number of cars. The results of this experiment with these situations are given latter on in the section results.

Table J10. Number of vehicles with an increase in cars

Zone	Distribution population	Car (806)	Car +10% (887)	Car +20% (967)	Car +30% (1048)	Bus share 20% (202)	Bus share 50% (806)
1	38%	306	337	367	398	77	306
2	16%	129	142	155	168	32	129
3	16%	129	142	155	168	32	129
4	29%	234	257	242	304	59	234
5	1%	8	9	10	11	2	8

J.2.2 Scenario Financial

Table J.11 gives the distribution of the population over the five zones on the Hicacos peninsula in scenario Financial. Table J.12 gives the distribution of vehicles according to the conditions in the current situation.

Table J.11 Distribution of population

Zone	Distribution types of people	Total population	Distribution population	Transported by Buses	Transported by car
1	56,000 tourists + 20,462 locals	76,462	37%	45,877	30,585
2	21,000 tourists + 14,324 locals	35,324	17%	21,194	14,130
3	21,000 tourists + 13,642 locals	34,642	16%	20,785	13,857
4	42,000 tourists + 17,734 locals	59,734	29%	35,840	23,894
5	2,046 locals	2,046	1%	1,228	818

Table J.12 Distribution of vehicles

Zone	Distribution population	Cars (806)	Bus 20% (202)	Bus50% (806)
1	37%	298	75	298
2	17%	137	34	137
3	16%	129	32	129
4	29%	234	59	234
5	1%	8	2	8

Table J13 shows the distribution of the population among in case 50% is transported by bus and 50% is transported by car. The results can be find in the section results of this appendix.

Table J13. Distribution of population 50% by bus and 50% by car

Zone	Distribution population	Bus	Car
1	76,462	38,231	38,231
2	35,324	17,662	17,662
3	34,642	17,321	17,321
4	59,734	29,867	29,867
5	2,046	1,023	1,023

Table J14 gives the number of vehicles with different increases in number of cars. The results of this experiment with these situations are given latter on in the section results.

Table J14. Number of vehicles with an increase in cars

Zone	Distribution population	Cars (806)	+10% Car (887)	+ 20% Car (967)	+30% Car (1048)	Bussen 20% (202)
1	37%	298	328	358	388	75
2	17%	137	151	164	178	34
3	16%	129	142	155	168	32
4	29%	234	257	280	304	59
5	1%	8	9	10	12	2

J.2.3 Scenario Linear trend

Table J.15 gives the distribution of the population over the five zones on the Hicacos peninsula in scenario Financial. Table J.16 gives the distribution of vehicles according to the conditions in the current situation.

Table J.15 Distribution of population

Zone	Distribution types of people	Total population	Distribution population	Transported by buses	Transported by car
1	30,000 tourists + 20,462 locals	50,462	35%	30,277	20,184
2	11,250 tourists + 14,324 locals	25,574	18%	15,344	10,230
3	11,250 tourists + 13,642 locals	24,892	17%	14,935	9,957
4	22,500 tourists + 17,734 locals	40,234	28%	24,140	16,094
5	2,046 locals	2,046	2%	1,228	818

Table J.16. Distribution of vehicles

Zone	Distribution population	Cars (806)	Bus 20% (202)	Bus 50% (806)
1	35%	282	72	282
2	18%	145	36	145
3	17%	137	35	137
4	28%	226	57	226
5	2%	16	2	16

Table J17 shows the distribution of the population among in case 50% is transported by bus and 50% is transported by car. The results can be find in the section results of this appendix.

Table J17. Distribution of population 50% by bus and 50% by car

Zone	Total population	Bus	Car
1	50,462	25,231	25,231
2	25,574	12,787	12,787
3	24,892	12,446	12,446
4	40,234	20,117	20,117
5	2,046	1,023	1,023

Table J18 gives the number of vehicles with different increases in number of cars. The results of this experiment with these situations are given latter on in the section results.

Table J18. Number of vehicles with an increase in cars

Zone	Distribution population	Cars (806)	+10% Car (887)	+20% Car (967)	+30% Car (1048)	Bussen 20% (202)
1	35%	282	310	338	367	72
2	18%	145	160	174	189	36
3	17%	137	151	164	178	35
4	28%	226	248	271	293	57
5	2%	16	18	19	21	2

Results

Table J19 gives the outcomes of the experiments done on the conditions of the current situation. Per scenario is one experiment done with four different situations.

Table J19. Outcomes of the forecasted scenarios based on the conditions in the current situation

	Current situation	Scenario MinTur	Scenario Financial	Scenario Linear
	Time [h]	Time [h]	Time [h]	Time [h]
Equally divided 20% buses	9.11	39.03	28.74	19.15
Equally divided 50% buses	9.11	39.03	28.74	19.15
Divided based on population 20%	7.79	26.69	19.78	13.33
Divided based on population 50%	7.78	26.85	19.91	13.28

Table J20 gives per scenario the evacuation time with different increases of the number cars.

Table J20. Outcomes of the forecasted scenarios with increases in number of cars.

	Scenario MinTur	Scenario Financial	Scenario Linear
	Time [h]	Time [h]	Time[h]
100% cars	25.98	19.69	13.87
+ 10% cars	23.67	17.94	12.69
+ 20% cars	22.48	16.67	11.69
+30% cars	22.47	16.61	11.16

K. Results Multi-Criteria Analysis

The multicriteria analysis in section 5.1 lists only the general protocol and the results. The steps towards calculating the MCA results are shown in this Appendix. Firstly, the criteria were determined:

Criteria for coastal intervention alternatives MCA	
Criterion	**Description**
1 Protection against erosion	
1.1 Normal conditions	Protection against erosion in normal conditions
1.2 Cold fronts	Protection against erosion due to cold fronts - frequent event.
1.3 Hurricanes	Protection against erosion due to hurricanes - extreme event.
2 Maintenance	
2.1 Nourishment	Frequency of required periodic nourishments
2.2 Structural	Robustness of the structures, number of predictable weak spots
2.3 Nuisance	Impact on recreation during maintenance
2.4 Complexity	Required submerged works and need for heavy equipment
3 Spatial quality	
3.1 Visual	Ocean view and visibility of structures
3.2 Beach	Dimension, capacity and attractiveness of the beach
4 Recreational quality	
4.1 Swimming	Safety, comfort and dimensions of the swimming zone
4.2 Miscellaneous	Added value through extra recreation possibilities
5 Construction	
5.1 Execution	Complexity and local experience with construction method and design
5.2 Material availability	Local availability of required materials
6 Environment	
6.1 Longshore transport	Facilitation of uninterrupted longshore transport
6.2 Fabrication and transport	Ecological impact associated with logistics and prefabrication
6.3 Biodiversity	Impact on biodiversity and possibility to create new livelihoods
7 Risks	
7.1 Complexity	Risk due to design or fabrication complexity

To quantify the performance of each method for these different criteria, a scale from one through five and a weight per category is assigned.

Specifcation valuation of coastal intervention MCA weight factors (1-5)	Minimal performance	Average performance	Maximum performance
1 Protection against erosion (4)			
1.1 Normal conditions	1: No protection	3: Partial protection	5: Full protection
1.2 Cold fronts	1: No protection	3: Partial protection	5: Full protection
1.3 Hurricanes	1: No protection	3: Partial protection	5: Full protection
2 Maintenance (1)			
2.1 Nourishment	1: Annually or more	3: After several extreme events	5: Once every five years
2.2 Structural	1: Degradable	3: Damageable	5: Lifetime stability
2.3 Nuisance	1: Recreation suspended	3: Low season nuisance	5: Recreation uninterrupted
2.4 Complexity	1: Heavy equipment	3: Handtools and nearshore personnel	5: Quick-fix
3 Spatial quality (4)			
3.1 Visual	1: Emerged structures	3: Intermittently emerged structures	5: Submerged structures
3.2 Beach	1: Minimal beach width	3: Minimal beach width, gentle slopes	5: Extra wide beach, gentle slopes
4 Recreational quality (3)			
4.1 Swimming	1: Hindered swimming	3: Structure adjacent swimming zone	5: Unhindered swimming
4.2 Miscellaneous	1: No extra recreation	3: Two added recreational options	5: Marine recreation dimension
5 Construction (3)			
5.1 Execution	1: Zero local know-how	3: Joint local-international venture	5: Locally executable
5.2 Material availability	1: Lacking basic materials	3: Some specialist items needed	5: All materials available in Cuba
6 Environment (2)			
6.1 Longshore sediment	1: Nuisance both directions	3: Nuisance one direction	5: No disruption of transport
6.2 Fabrication/transport	1: International transport	3: Regional transport	5: Locally fabricated
6.3 Biodiversity	1: No or adverse effect	3: Slight biological stimulus	5: Habitat creation
7 Risks (1)			
7.1 Complexity	1: Uncertainties in design	3: Uncertainties in execution	5: Common method

The following scores have been given to the various model. Each table corresponds to one of the seven main criteria. The last table represents the total scores, as indicated in the summarised version of the MCA in the main text of this report.

Alternative	1 Protection against erosion			
Weight factor	1.1	1.2	1.3	Total
1: Nourishment	1	1	1	**3**
2: Artificial reef	4	4	2	**10**
3: Submerged breakwater	3	5	3	**11**
4: Combined	5	3	4	**12**

Alternative	2 Maintenance				
Weight factor	2.1	2.2	2.3	2.4	Total
1: Nourishment	1	1	1	1	**4**
2: Artificial reef	4	3	4	2	**13**
3: Submerged breakwater	5	5	3	3	**16**
4: Combined	4	4	3	3	**14**

Alternative	3 Spatial quality		
Weight factor	3.1	3.2	Total
1: Nourishment	5	3	**8**
2: Artificial reef	5	3	**8**
3: Submerged breakwater	3	2	**5**
4: Combined	3	2	**5**

Alternative	4 Recreational quality		
Weight factor	4.1	4.2	Total
1: Nourishment	5	1	**6**
2: Artificial reef	4	5	**9**
3: Submerged breakwater	4	1	**5**
4: Combined	4	5	**9**

Alternative	5 Construction		
Weight factor	5.1	5.2	Total
1: Nourishment	4	4	**8**
2: Artificial reef	3	3	**6**
3: Submerged breakwater	2	3	**5**
4: Combined	2	3	**5**

Alternative	6 Environment			
Weight factor	6.1	6.2	6.3	Total
1: Nourishment	3	5	1	**9**
2: Artificial reef	3	3	5	**11**
3: Submerged breakwater	1	4	2	**7**
4: Combined	1	3	5	**9**

Alternative	7 Risks	
Weight factor	7.1	Total
1: Nourishment	2	**2**
2: Artificial reef	5	**5**
3: Submerged breakwater	4	**4**
4: Combined	5	**5**

Criterion	Protection			Recreation	Construction			Total Score
Weight factor:	4	1	4	3	3	2	1	
1: Nourishment	12	4	32	18	24	18	4	**112**
2: Artificial reef	40	13	32	27	18	22	2	**154**
3: Submerged breakwater	44	16	20	15	15	14	4	**128**
4: Combined	48	14	20	27	15	18	3	**145**

L. Coral reefs

Figure L1. Acropora palmata coral platen on a Reef Ball ™

Figure L1 shows a sample of planted Acropora palmata which had grown to this size in about 2 years. Stimulation of these types of coral can quickly result in enhanced coastal protection due to their vertical topography and stony nature.

Figure L2: Biodiversity on a Reef Ball ™

Figure L2 shows an example of successful biodiversification, which was the objective in the placement of this unit. However, this result would be unfit for the use of coastal protection as little vertical topography is achieved and soft corals have settled practically on the entire Reef Ball ™ surface. Alteration of hydrodynamics superseding the initial capacity of the elements is thus negligible.

Figure L3: Floatation of the Reef Ball ™

A five-man snorkel crew is more than sufficient for guiding the Reef Ball ™ units to their destined location. The black bags in the ball holes are the flotation bladders. These will be punctured and removed upon submersion (Figure L3). A two-man crew onshore will ensure placement of the units at MSL. An extra diver with pneumatic hammer will be employed to fixate the outer reef elements to the seafloor. This brings the total crew to 8 members. Two of such crews will be deployed in 'Durable Development of Oasis Beach'.

Figure L4: Coral pontoon boat with crew

An example of a simple coral pontoon is given in figure L4. A small vessel, like the one in the background, can be used to tow the pontoon into position where divers can be employed to cover a sizeable area. Materials aboard include: fragmentation tools, latex gloves, coral epoxy putty, plug cement, thermometers, oil free sunblock, dissolved oxygen test kits, antibacterial soap, partially submerged coral trays and any other item necessary for the specific task. Crew members in Figure L4: table boss (left), wet handler (back) and dry handler (front).

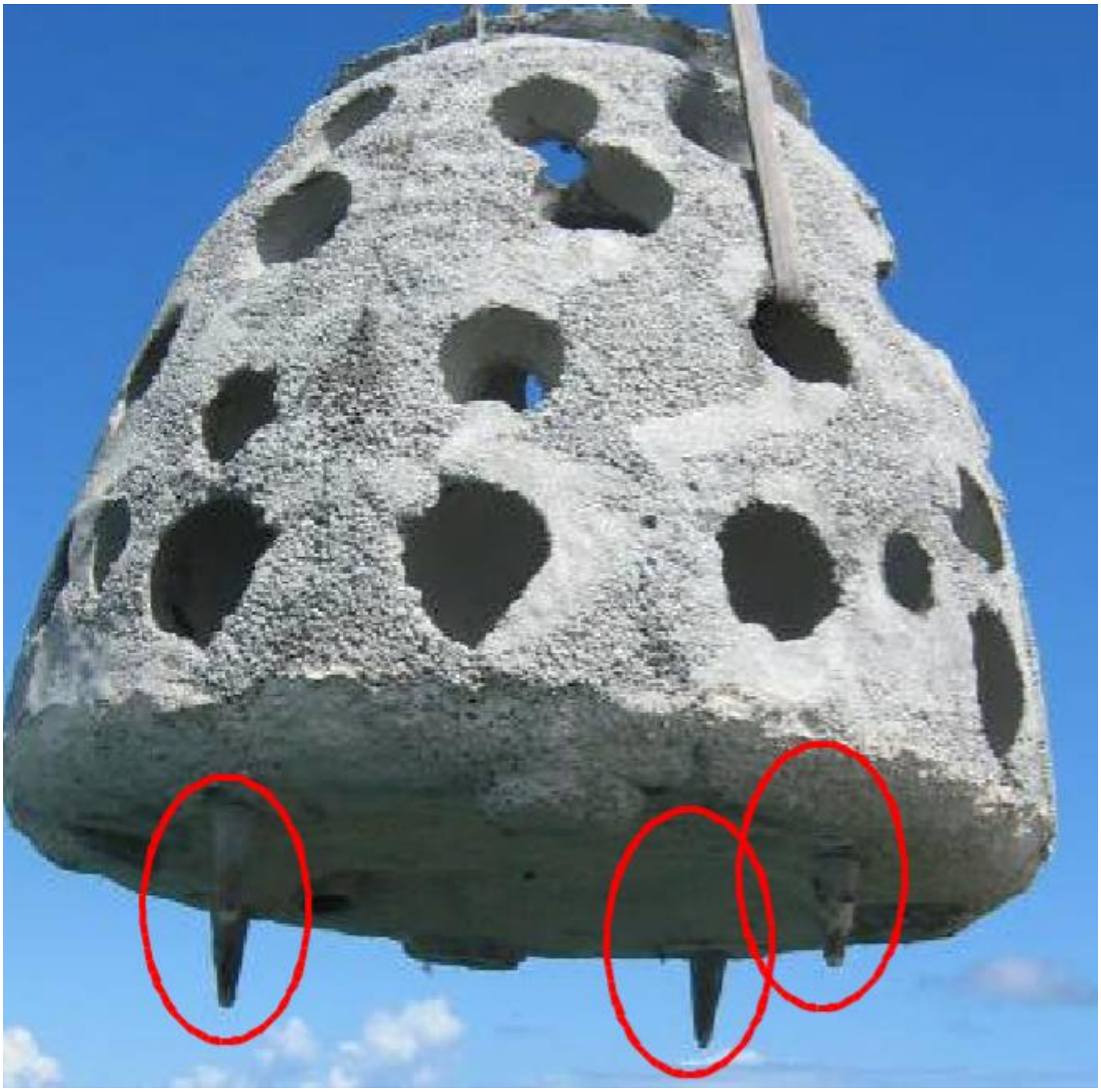


Figure L5: Fibre glass rebar foundation spikes under a Goliath Reef Ball ™

Pre-installed glass fibre rebar spikes are shown in Figure M5. These can be used in hard bottom conditions as is the case for Oasis beach. Sufficient length should be achieved to penetrate the thin layer of nourished sediment. Post-installation of rebar spikes is applied in higher wave energy climates. This is because instalment needs to be done under a 45-degree angle and proper alignment is more critical. Hence, post-instalment is preferred at Oasis beach.

Figure L6: Foundation pile installation on a layer cake element

A snorkel crew-member installing a fibre rebar under water for a 'layer cake' unit. This process is performed in similar fashion for Reef Balls ™. Pre-drilled holes are present on the seafloor and directed at 45-degree angles to effectively combat wave pressure and suction due to return currents.

M. Final design – Western groyne

This appendix gives the full detailed final design of the western groyne.

Final design western groyne		
Geography & Bathymetry	**Design**	**Notes**
Length:	110 m	Dune foot
Distance offshore:	80 m	
Option submerged extension	25 m	Sheltered solution
Depth:	-2.5 m MSL	Maximum
Geometry of the cross-section		
Structure height:	MSL	at -5 m MSL
Crest width:	3.0 m	Oasis 2014
Slope angle:	1:2	
Material (Dn50)		
Armour stone W:	1.57 m	Rep. size
Armour stone E (exposed):	1.47 m	
Armour stone E (sheltered):	0.53 m	Combined solution
First sub layer:	0.63 m	1/2.5
Filter layer:	0.25 m	1/2.5
Core:	66 - 90 μm	Cayo Mono coarse
Bulk volume:	6588 - 7511.4 m^3	Sheltered/exposed
Layer thickness		
Armour stone W:	3.14 m	
Armour stone E (exposed):	2.93 m	
Amrou stone E (sheltered):	1.06 m	Combined solution
First sub layer:	1.26 m	1/2.5
Filter layer:	0.50 m	1/2.5
Core:	361.4 m^3	Cayo Mono coarse
Toe		
Relative toe depth:	0.5 [-]	ht/h
Diameter W:	0.83 m	
Diameter E (exposed):	0.67 m	
Diameter E (sheltered):	0.53 m	Imposed minimum
Hydronamics		
Waves W - NW:	4.93 m	Depth-induced
Waves NE - E (exposed):	4.00 m	Depth-induced
Waves NE - E (sheltered):	1.20 m	Combined solution
Max. set-up:	1.16 m	Tide and surge

Bulk concrete volume - Western groyne		
Toe	**Design**	**Notes**
Cross section W	4.13 m²	
Cross section E (exposed)	2.69 m²	
Cross section E (sheltered)	1.68 m²	
Toe volume (exposed)	750.2 m³	2350 kg/m³
Toe volume (sheltered)	639.1 m³	2350 kg/m³
Armour layer		
Cross section armour (exposed)	59.1 m²	
Volume armour (exposed)	6500 m³	2350 kg/m³
Cross section armour (sheltered)	48.6 m²	
Volume armour (sheltered)	5340 m³	2350 kg/m³
Underlayer		
Cross section underlayer	9.59 m²	
Volume underlayer	1054.7 m³	2350 kg/m³
Filter layer:		
Cross section filter layer	4.34 m²	
Volume filter layer	477.6 m³	2350 kg/m³
Core		
Average dross section core	3.3 m²	Function of x
Total sand volume	361.4 m³	Cayo Mono coarse
Total volume		
Average cross section excl. core (exposed)	79.9 m²	
Average cross section excl. core (sheltered)	68.3 m²	
Total length	110 m	80 m offshore
Bulk concrete volume (Exposed)	6588.0 m³	2350 kg/m³
Bulk concrete volume (Sheltered)	7511.4 m³	2350 kg/m³
Concrete savings by exposing	923.4 m³	

Bulk concrete volume - submerged breakwater		
Toe	**Design**	**Notes**
Cross section N	5.57 m^2	
Cross section S	5.57 m^2	
Cross section total	11.1 m^2	
Toe volume	8800 m^3	2350 kg/m^3
Armour layer		
Cross section armour	37.29 m^2	
Volume armour	29,832 m^3	2350 kg/m^3
Underlayer		
Cross section underlayer	14.51 m^2	
Volume underlayer	11,608 m^3	2350 kg/m^3
Filter layer:		
Cross section filter layer	7.44 m^2	
Volume filter layer	5,952 m^3	2350 kg/m^3
Core		
Cross section core	30.86 m^2	Optional: rubble
Total sand volume	24,688 m^3	Cayo Mono coarse
Total volume		
Total cross section excl. core	64.81 m^2	
Total length	800 m	
Bulk concrete volume	51,848 m^3	2350 kg/m^3

Bulk concrete volume - Elongated Paso Malo channel		
Toe	**Design**	**Notes**
Cross section W (sheltered)	1.68 m^2	
Cross section E (exposed)	4.13 m^2	
Toe volume (sheltered)	6.72m^2	
Toe volume (exposed)	16.52 m^3	2350 kg/m^3
Armour layer		
Cross section armour (exposed)	59.1 m^2	
Volume armour (exposed)	2364 m^3	2350 kg/m^3
Cross section armour (sheltered)	48.6 m^2	
Volume armour (sheltered)	1944 m^3	2350 kg/m^3
Underlayer		
Cross section underlayer	9.59 m^2	
Volume underlayer	383.6 m^3	2350 kg/m^3
Filter layer:		
Cross section filter layer	4.34 m^2	
Volume filter layer	173.6 m^3	2350 kg/m^3
Core		
Cross section core	3.3 m^2	Optional: rubble
Total sand volume	132 m^3	Cayo Mono coarse
Total volume		
Average cross section excl. core (exposed)	79.9 m^2	
Average cross section excl. core (sheltered)	68.3 m^2	
Total length	40 m	
Bulk concrete volume (Exposed)	3196 m^3	2350 kg/m^3
Bulk concrete volume (Sheltered)	2732 m^3	2350 kg/m^3
Concrete savings by exposing	464 m^3	

N. Cost estimation

The cost estimations used in the solutions coastal development section are elaborated in this Appendix. It is concluded with a cost summary, in which the final costs of the three solutions are noted.

Cost estimation demolition

Demolition				
	Specification	**Quantitiy**	**Price/unit**	**Costs**
Primary cost				
C1 Direct cost of material				
1.1 Load of demolition	Debris	1700 m³	$0.02	$41.08
			Total:	$41.08
C2 Direct cost of labour				
2.1 Design	-	160 hours	$0.17	$26.67
2.2 Preparation	-	960 hours	$0.15	$140.00
2.3 Execution	-	1200 hours	$0.15	$175.00
			Total:	$341.67
C3 Direct cost of equipment				
3.1 Crane	-	132 hours	$0.73	$96.91
3.2 Hammer	-	1700 m³	$2.37	$4,025.46
3.3 Bulldozer	-	120 hours	$1.29	$154.80
3.4 Fuel (2 machines)	-	1100 litres	$0.83	$916.67
			Total:	$5,193.84
C4 Direct cost of support and minor materials			Total:	$167.30
C5 Total direct cost			Total:	$5,743.88
C6 Indirect cost			Total:	$1,665.73
C7 Profit			Total:	$1,471.00
C8 Total primary cost			Total:	$8,880.61
Secondary cost				
P1 Temporary facilities				
1.2 Toilets, warehouses etc.	-	20 days	$20.00	$400.00
			Total:	$400.00
P2 Transport				
2.1 Materials by truck (10 m³ each)	Price per 100 m³	1700 m³	$3.36	$57.04
2.2 Additional trucking distance (1 km)	If disposed at all	663 km	$0.81	$534.82
2.3 Equipment by heavy trucks		24 hours	$1.25	$30.00
			Total:	$621.86
P3 Other additional cost				
3.1 Beachfront cleaning	10 persons	24 hours	$0.13	$30.00
			Total:	$30.00
P4 Banking				
4.1 Interest salaries	10	% of C2		$34.17
4.2 Interest investment	2	% of C8-C2		$170.78
			Total:	$204.95
P5 Insurance	10	% of C5	Total:	$574.39
P6 Unforeseen cost				
6.1 Flawed cost estimation risk	2	% of C8+P1,2,3		$190.65
6.2 Flawed time estimation risk	5	% of T*(C2+C3)/Tp		$276.78
			Total:	$467.42
P7 Total secondary cost			Totlal:	$2,298.61
P8 Total capital costs			Total:	$11,179.23

Initial nourishment

Initial nourishment					
		Specification	Quantitiy	Price/unit	Costs
Primary cost					
C1	Direct cost of material				
1.1	Sand	Cayo Mono borrowing zone	79.000 m³	$0.02	$1,909.17
				Total:	$1,909.17
C2	Direct cost of labour				
2.1	Design	Adopted from 2014	86 hours	$0.17	$14.33
2.2	Preparation	Adopted from 2014	480 hours	$0.15	$70.00
2.3	Execution	Scaled to 2014 volume	4200 hours	$0.15	$612.50
				Total:	$696.83
C3	Direct cost of equipment				
3.1	Tugboat	Scaled to 2014 volume	70 hours	$0.73	$51.39
3.2	Pipeline	Adopted from 2014	1000 m	$2.37	$2,367.92
3.3	Bulldozer	Scaled to 2014 volume	45 hours	$1.29	$58.05
3.4	Fuel (2 machines)	Scaled to 2014 volume	370 litres	$0.83	$308.33
				Total:	$2,785.69
C4	Direct cost of support and minor materials			Total:	$161.75
C5	Total direct cost			Total:	$5,553.44
C6	Indirect cost			Total:	$1,610.50
C7	Profit			Total:	$925.45
C8	Total primary cost			Total:	$8,089.39
Secondary cost					
P1	Temporary facilities				
1.2	Toilets, warehouses etc.	Adopted from 2014	10 days	$20.00	$200.00
				Total:	$200.00
P2	Transport				
				Total:	$0.00
P3	Other additional cost				
3.1	Beachfront cleaning	10 persons	24 hours	$0.13	$30.00
				Total:	$30.00
P4	Banking				
4.1	Interest salaries	10	% of C2		$69.68
4.2	Interest investment	2	% of C8-C2		$147.85
				Total:	$217.53
P5	Insurance	10	% of C5	Total:	$555.34
P6	Unforeseen cost				
6.1	Flawed cost estimation risk	2	% of C8+P1,2,3		$162.39
6.2	Flawed time estimation risk	5	% of T*(C2+C3)/Tp		$174.13
				Total:	$336.51
P7	Total secondary cost			Totlal:	$1,339.39
P8	Total capital costs			Total:	$9,428.78

Cost estimation Western groyne not sheltered

Groyne not sheltered by submerged breakwater

		Specification	Quantitiy	Price/unit	Costs
		Primary cost			
C1	Direct cost of material				
1.1	Concrete	Cuban maximum cost	6588 m³	$9.27	$70,206.12
1.2	Sand	Cayo Mono coarse diameter	271.1 m³	$0.02	$6.55
				Total:	$70,212.67
C2	Direct cost of labour				
2.1	Design	Cuban engineers (4)	4200 hours	$0.17	$700.00
2.2	Preparation	Surveying, factory production	1800 hours	$0.17	$300.00
2.3	Construction	Construction workers (10)	12000 hours	$0.15	$1,750.00
2.4	Inspection	Cuban engineers (2)	100 hours	$0.17	$16.67
				Total:	$2,766.67
C3	Direct cost of equipment				
3.1	Truck + crane	Nearshore construction (35%)	4073 hours	$0.72	$2,925.77
3.2	Barge	Offshore construction (65%)	7127 hours	$8.33	$59,391.67
3.4	Fuel (50 litres / unit / day)	140 days, 2 units	14000 litres	$0.83	$11,666.67
				Total:	$73,984.11
C4	Direct cost of support and minor materials			Total:	$4,408.90
C5	Total direct cost			Total:	$151,372.35
C6	Indirect cost			Total:	$43,897.98
C7	Profit			Total:	$20,395.75
C8	Total primary cost			Total:	$215,666.08
		Secondary cost			
P1	Temporary facilities				
1.2	Toilets, warehouses etc.	-	150 days	$20.00	$3,000.00
				Total:	$3,000.00
P2	Transport				
2.1	Material by truck	Per 10m³ for 1km (35%)	2306 m³	$0.34	$773.47
2.2	Material by barge	Per 10m³ for 1km (65%)	4282 m³	$0.83	$3,568.33
2.3	Additional trucking distance	per km, 350 km return, 30 m³	79 trips	$0.08	$2,235.04
2.4	Additional boating distance (5 crew)	per km, 320 km return, 500m³	9 trips	$0.40	$1,164.00
				Total:	$7,740.85
P3	Other additional cost				
3.1	Cleaning	10 persons	400 hours	$0.15	$58.33
				Total:	$58.33
P4	Banking				
4.1	Interest salaries	10	% of C2		$276.67
4.2	Interest investment	2	% of C8-C2		$4,257.99
				Total:	$4,534.65
P5	Insurance	10	% of C5	Total:	$15,137.23
P6	Unforeseen cost				
6.1	Flawed cost estimation risk	2	% of C8+P1,2,3		$4,469.31
6.2	Flawed time estimation risk	5	% of T*(C2+C3)/Tp		$5,852.25
				Total:	$10,321.55
P7	Total secondary cost			Totlal:	$40,792.62
P8	Total capital costs			Total:	$256,458.70

Cost estimation Western groyne sheltered

Groyne sheltered by submerged breakwater				
	Specification	**Quantitiy**	**Price/unit**	**Costs**
Primary cost				
C1 Direct cost of material				
1.1 Concrete	Cuban maximum cost	7511.4 m³	$9.27	$80,046.49
1.2 Sand	Cayo Mono coarse diameter	361.4 m³	$0.02	$8.73
			Total:	$80,055.22
C2 Direct cost of labour				
2.1 Design	Cuban engineers (4)	4200 hours	$0.17	$700.00
2.2 Preparation	Surveying, factory production	1600 hours	$0.17	$266.67
2.3 Construction	Construction workers (10)	11200 hours	$0.15	$1,633.33
2.4 Inspection	Cuban engineers (2)	100 hours	$0.17	$16.67
			Total:	$2,616.67
C3 Direct cost of equipment				
3.1 Truck + crane	Nearshore construction (35%)	4073 hours	$0.72	$2,925.77
3.2 Barge	Offshore construction (65%)	7127 hours	$8.33	$59,391.67
3.4 Fuel (50 litres / unit / day)	140 days, 2 units	14000 litres	$0.83	$11,666.67
			Total:	$73,984.11
C4 Direct cost of support and minor materials			Total:	$4,699.68
C5 Total direct cost			Total:	$161,355.67
C6 Indirect cost			Total:	$46,793.14
C7 Profit			Total:	$20,355.89
C8 Total primary cost			Total:	$228,504.70
Secondary cost				
P1 Temporary facilities				
1.2 Toilets, warehouses etc.	-	140 days	$20.00	$2,800.00
			Total:	$2,800.00
P2 Transport				
2.1 Material by truck	Per 10m³ for 1km (35%)	2629 m³	$0.34	$881.81
2.2 Material by barge	Per 10m³ for 1km (65%)	4882 m³	$0.83	$4,068.33
2.3 Additional trucking distance	per km, 350 km return, 30 m³	88 trips	$0.08	$2,489.67
2.4 Additional boating distance (x5)	per km, 320 km return, 500m³	10 trips	$0.40	$1,293.33
			Total:	$8,733.14
P3 Other additional cost				
3.1 Cleaning	10 persons	400 hours	$0.15	$58.33
			Total:	$58.33
P4 Banking				
4.1 Interest salaries	10	% of C2		$261.67
4.2 Interest investment	2	% of C8-C2		$4,517.76
			Total:	$4,779.43
P5 Insurance	10	% of C5	Total:	$16,135.57
P6 Unforeseen cost				
6.1 Flawed cost estimation risk	2	% of C8+P1,2,3		$4,745.92
6.2 Flawed time estimation risk	5	% of T*(C2+C3)/Tp		$5,840.81
			Total:	$10,586.73
P7 Total secondary cost			Totlal:	$43,093.20
P8 Total capital costs			Total:	$271,597.91

Artificial Reef

	Specification	Quantitiy	Price/unit	Costs
Primary cost				
C1 Direct cost of material				
1.1 Substrate	Cuban maximum cost + 15%	2000 m³	$9.27	$21,313.33
1.2 Goliath Ball moulds ™	Reef Ball Foundation + 5%	4 units	$8,925.00	$36,592.50
1.3 Coral juveniles	Cuban maximum cost	20000 units	$1.00	$20,000.00
1.4 Fibreglass rebar anchors (short)	Reef Ball Foundation	3224 units	$25.00	$80,600.00
			Total:	$158,505.83
C2 Direct cost of labour				
2.1 Design	Cuban (2 hydro 2 biomarine)	7200 hours	$0.17	$1,200.00
2.2 Preparation	Goliath Ball ™, coral collection	832 hours	$0.15	$121.33
2.3 Deployment	Cuban (8 snorkle, 4 onshore)	12672 hours	$0.15	$1,848.00
2.4 Coral planting	Cuban (10 expert divers)	3584 hours	$0.15	$522.67
			Total:	$3,692.00
C3 Direct cost of equipment				
3.1 Truck + crane	Cuban	12672 hours	$0.72	$9,102.72
3.2 Contractor tool kit	Reef Ball Foundation	1 per dive squad	$200.00	$400.00
3.3 Coral Propagation & Planting kit	Reef Ball Foundation	1 per dive squad	$1,200.00	$2,400.00
3.4 Fuel (50 litres / unit / day)	Port Mariel - Oasis Beach	200.000 litres	$0.83	$166,666.67
3.5 Pneumatic drills	Anchoring (8 snorklers)	8 units	$400.00	$3,200.00
			Total:	$181,769.39
C4 Direct cost of support and minor materials			Total:	$10,319.02
C5 Total direct cost			Total:	$354,286.24
C6 Indirect cost			Total:	$102,743.01
C7 Profit			Total:	$49,284.51
C8 Total primary cost			Total:	$506,313.75
Secondary cost				
P1 Temporary facilities				
1.2 Toilets, warehouses etc.	-	244 days	$0.23	$55.92
			Total:	$55.92
P2 Transport				
2.1 Reef Ball Foundation shipment	Sarasota (FL) -Varadero	484 km	$0.93	$451.50
2.2 Material by truck	Per 10m³ for 1km	2000 m³	$0.34	$67.08
2.3 Additional trucking distance	per km, 350 km return trip	667 trips	$0.08	$18,861.17
2.4 Material by boat	Coral collection max. 90 km	6 trips	$0.83	$450.00
			Total:	$19,829.75
P3 Other additional cost				
3.1 Bedrock clearing	10 persons	360 hours	$0.15	$52.50
3.2 Inspection	4 biomarine engineers	320 hours	$0.17	$53.33
			Total:	$105.83
P4 Banking				
4.1 Interest salaries	10	% of C2		$369.20
4.2 Interest investment	2	% of C8-C2		$10,052.44
			Total:	$10,421.64
P5 Insurance	10	% of C5	Total:	$35,428.62
P6 Unforeseen cost				
6.1 Flawed cost estimation risk	2	% of C8+P1,2,3		$10,524.99
6.2 Flawed time estimation risk	5	% of T*(C2+C3)/Tp,c		$14,141.43
			Total:	$24,666.42
P7 Total secondary cost			Totlal:	$90,508.17
P8 Total capital costs			Total:	$596,821.93

Cost estimation submerged breakwate

Submerged breakwater				
	Specification	**Quantitiy**	**Price/unit**	**Costs**
		Primary cost		
C1 Direct cost of material				
1.1 Concrete	Incl. Paso Malo extension	54,074 m^3	$9.27	$501,085.73
1.2 Sand	Cayo Mono + Paso Malo ext.	24795 m^3	$0.02	$599.21
			Total:	$501,684.95
C2 Direct cost of labour				
2.1 Design	Cuban engineers (6), 60d	2880 hours	$0.17	$480.00
2.2 Preparation	Material acquisition (10), 30d	2400 hours	$0.15	$350.00
2.3 Execution	2014, 25 crew, Paso malo ext.	60000 hours	$0.15	$8,750.00
			Total:	$9,580.00
C3 Direct cost of equipment				
3.1 Tugboat	25% of works + Paso Malo ext.	15340 hours	$0.73	$11,262.12
3.2 Pipeline	Adopted from 2014	1000 m	$2.37	$2,367.92
3.3 Barges (4)	75% of works + Paso malo ext.	44600 hours	$8.33	$371,666.67
3.4 Fuel (5 machines)	50 l/machine/day	75000 litres	$0.83	$62,500.00
			Total:	$447,796.70
C4 Direct cost of support and minor materials			Total:	$28,771.85
C5 Total direct cost			Total:	$987,833.50
C6 Indirect cost			Total:	$286,471.71
C7 Profit			Total:	$121,543.28
C8 Total primary cost			Total:	$1,395,848.49
		Secondary cost		
P1 Temporary facilities				
1.2 Toilets, warehouses etc.	Shared cost	283 days	$20.00	$0.00
			Total:	$0.00
P2 Transport				
			Total:	$0.00
P3 Other additional cost				
3.1 Diver inspection	4 persons	24 hours	$0.17	$16.00
			Total:	$16.00
P4 Banking				
4.1 Interest salaries	10	% of C2		$958.00
4.2 Interest investment	2	% of C8-C2		$27,725.37
			Total:	$28,683.37
P5 Insurance	10	% of C5	Total:	$98,783.35
P6 Unforeseen cost				
6.1 Flawed cost estimation risk	2	% of C8+P1,2,3		$27,917.29
6.2 Flawed time estimation risk	5	% of T*(C2+C3)/T		$22,868.84
			Total:	$50,786.12
P7 Total secondary cost			Totlal:	$178,268.84
P8 Total capital costs			Total:	$1,574,117.34

Maintenance nourishment

Maintenance nourishment					
		Specification	Quantitiy	Price/unit	Costs
		Primary cost			
C1	Direct cost of material				
1.1	Sand	Cayo Mono borrowing zone	15.000 m^3	$0.02	$362.50
				Total:	$362.50
C2	Direct cost of labour				
2.1	Design	Same as initial nourishment	86 hours	$0.17	$14.33
2.2	Preparation	Same as initial nourishment	480 hours	$0.15	$70.00
2.3	Execution	Scaled to initial nourishment	797 hours	$0.15	$116.23
				Total:	$200.56
C3	Direct cost of equipment				
3.1	Tugboat	Scaled to initial nourishment	14 hours	$0.73	$10.28
3.2	Pipeline	Adopted from 2014	1000 m	$2.37	$2,367.92
3.3	Bulldozer	Same as initial nourishment	45 hours	$1.29	$58.05
3.4	Fuel (2 machines)	Scaled to 2014 volume	190 litres	$0.83	$158.33
				Total:	$2,594.58
C4	Direct cost of support and minor materials			Total:	$94.73
C5	Total direct cost			Total:	$3,252.37
C6	Indirect cost			Total:	$943.19
C7	Profit			Total:	$742.78
C8	Total primary cost			Total:	$4,938.34
		Secondary cost			
P1	Temporary facilities				
1.2	Toilets, warehouses etc.	Bulldozer crew	6 days	$20.00	$120.00
				Total:	$120.00
P2	Transport				
				Total:	$0.00
P3	Other additional cost				
3.1	Beachfront cleaning	10 persons	24 hours	$0.13	$30.00
				Total:	$30.00
P4	Banking				
4.1	Interest salaries	10	% of C2		$20.06
4.2	Interest investment	2	% of C8-C2		$94.76
				Total:	$114.81
P5	Insurance	10	% of C5	Total:	$325.24
P6	Unforeseen cost				
6.1	Flawed cost estimation risk	2	% of C8+P1,2,3		$99.37
6.2	Flawed time estimation risk	5	% of T*(C2+C3)/Tp		$139.76
				Total:	$239.12
P7	Total secondary cost			Totlal:	$829.17
P8	Total capital costs			Total:	$5,767.51

Cost summary

The cost estimation of the three solutions are given in the table below. As can be seen, all solutions firstly must demolish the hard structures on the beach, construct the Western groyne and perform an initial nourishment. Furthermore, all nourishments costs during their lifetime are incorporated in the final cost estimation.

Artificial Reef		
A1 Total cost of demolition	Total:	$11,255.51
B1 Total cost of nourishment	Total:	$9,383.71
C1 Total cost of maintenance nourishments (1, 6)	Total:	$34,716.59
D1 Total cost of western groyne	Total:	$256,458.62
E1 Total cost of artificial reef	Total:	$596,821.93
F1 Total cost of intervention	Total:	$908,636.35

Artificial reef and submerged breakwater		
A2 Total cost of demolition	Total:	$11,255.51
B2 Total cost of nourishment	Total:	$9,383.71
C2 Total cost of maintenance nourishments (1, 6)	Total:	$34,716.59
D2 Total cost of western groyne	Total:	$271,597.91
E2 Total cost of artificial reef	Total:	$596,821.93
F2 Total cost of submerged breakwater	Total:	$1,574,117.34
G2 Total cost of intervention	Total:	$2,497,892.98

Submerged breakwater		
A3 Total cost of demolition	Total:	$11,255.51
B3 Total cost of nourishment	Total:	$9,383.71
C3 Total cost of maintenance nourishments (0, 6)	Total:	$28,951.08
D3 Total cost of western groyne	Total:	$271,597.91
E3 Total cost of submerged breakwater	Total:	$1,574,117.34
F3 Total cost of intervention	Total:	$1,895,305.54